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Bachelor's Degree in Energy Engineering
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Bachelor's Thesis

Study of the effects of Organic Rankine Cycles on Biomass Combustion Power Plant performance

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1. MOTIVATION AND OBJECTIVES

1.1) Introduction

As the world develops it becomes more evident the energy dependency due to the rising global energy demand. Increasing energy consumption brings with it larger releases of CO_2, which intensifies concerns about Climate Change. According to the IEA the world needs a clean energy revolution so that dependence on fossil fuels breaks. In this way, it could be also broken the long-standing link between economic growth and CO_2 emissions. Renewable energy appears as the most promising way to reduce fossil fuels consumption which leads to pollution mitigation.

The European Union strongly supports secure, competitive and sustainable energy so they have developed an EU Energy Strategy, which targets (with respect to 1990) are:

- ✓ A 20%, 40% and 80-95% **cut in greenhouse gases (GHG) emissions** for 2020, 2030 and 2050 respectively.
- ✓ At least 20%, 27%, **share of renewable energy consumption** for 2020 and 2030 respectively.
- ✓ A 20%, 27% **improvement in energy efficiency** for 2020 and 2030 respectively.

According to [1] and as it can be observed in Figure 1, EU is well on track towards meeting the objective regarding share of renewable energy consumption as it accounted for 16,4% of net electricity generation in 2015.

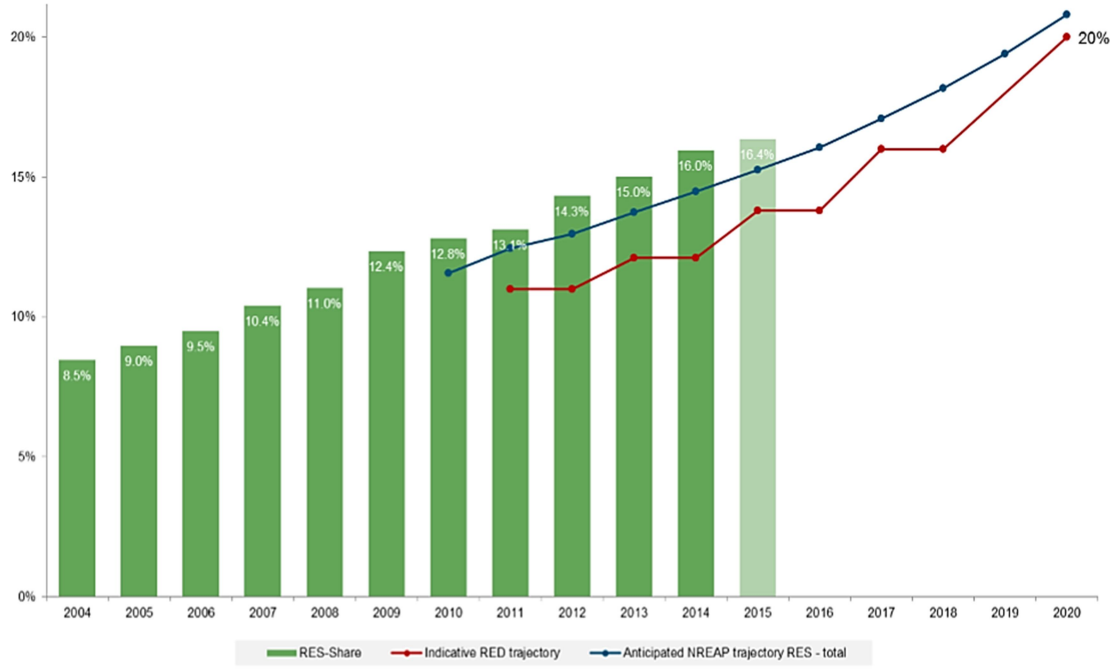


Figure 1: Renewable energy shares in the EU vs. Renewable Energy Directive (RED) and National Energy Action Plan (NREAP) trajectories (based on EUROSTAT, Öko-Institut) [1]

Although it is clear clean energy technologies have suffered an important progress in recent years, this fact is being outshone by the surging demand of fossil fuels. In 2015, according to [2], fossil fuels accounted for 48,1% of total net electricity generated, almost one half of it, being the major contributor to net electricity production.

In this context, the development and improvement of new conversion technologies to take further advantage of renewable energy sources becomes a necessity to shift from fossil fuel electricity generation towards renewable energies.

This is the background where Organic Rankine Cycles (ORC) can play a significant role, contributing to reduce energy losses and GHG emissions so that it promotes competitiveness and sustainability in energy supply. Basically, it consists on increasing energy produced for the same amount of pollutants. The main advantage of ORCs is that they can convert heat at low temperatures into electricity, enabling a better usage of primary energy. According to this, Organic Rankine Cycles have the possibility to be implemented in decentralized power plants with lower capacity, so they are well suited for small scale power generation. For these reasons, ORC appear as a technology very convenient for the conversion of renewable energy sources, as its temperature is lower than that of fossil fuels.

1.2) Motivation

Among the renewable sources to achieve an optimal ORC, mainly geothermal, solar or biomass heat sources are included, as well as waste heat recovery (from industrial processes, internal combustion engines…).

On 21 April 2017, United Kingdom went without coal power for 24 hours as reported by the National Grid, the electric grid system operator.

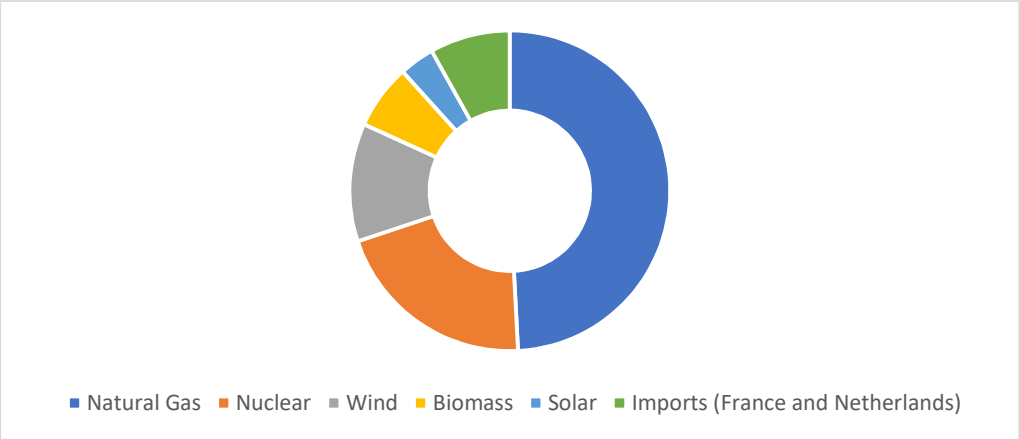


Figure 2: Generation mix on United Kingdom, 21/04/17, free coal day [3]

As it can be appreciated in Figure 2, it was reported by [3] that biomass played a significant role in making possible this coal-free day, as it accounted for 6.7% of the generation mix. This is a proof supporting biomass as an important substitute of fossil fuels having the advantage of being sustainable and environmentally friendly. For this reason this project will establish biomass combustion as the renewable source for the ORC.

Biomass is a source that can be found available in many processes; it is derived from organic material coming mainly from trees, plants and agriculture or industrial processes such as wood industry or urban solid waste. According to [4] an increase in the use of biomass in the EU would help to diversify energy supply, would create growth and jobs and would reduce GHG emissions.

From the different studies trying to estimate biomass potential it is deducted that biomass is well suited for decentralized medium-small scale Combined Heat and Power (CHP). The main reasons are the reduction in transportation costs if used on site and the difficulty of finding a large-end user requiring the amount of heat of a large-scale CHP plant [5].

Electric efficiencies of ORC ranges between 6 and 17% but although it is quite low, according to literature these plants require low maintenance work, which means low personnel and O&M costs [5] among other advantages that will be analyzed later in detail. Due to the low electric efficiencies and to ensure the profitability of the investment CHP becomes a good option as it increases conversion efficiencies by contributing to the local heat demand for industrial processes such as wood drying or district or industrial heating [6].

Although ORCs have been investigated since 80s they have never been popular until now due to the rising interest on medium and low grade energy recovery where water is not suitable as working fluid due to technical and economic reasons [5]. As it operates like a conventional Steam Rankine Cycle (SRC) with similar layout and components and due to all the advantages previously mentioned it becomes interesting to perform a detailed study of these plants and the ways to improve them in terms of configuration and design parameters.

The fluid selection means one of the key factors to make the plant viable so it is necessary to carry out an analysis of the different organic fluids available and suitable to find the optimum for the plant designed, as well as the optimum cycle configuration.

1.3) Objectives

Being motivated by the renewable origin of biomass and the possibility of electricity generation in a small scale to reduce GHG emissions, the project objectives will consist on:

- ✓ Understanding what biomass refers to, analyzing it as an energy source in terms of advantages and disadvantages, properties and processes it suffers that lead to energy generation.
- ✓ Getting to know and understand functioning of biomass power plants as well as the main elements and processes taking place in them.
- ✓ Analyzing ORCs highlighting the advantages and disadvantages it brings with respect to traditional steam rankine cycles, studying its application for biomass source, which is the main scope, and understanding its principal aspects as well as its situation in the market.

To accomplish these objectives the project will be built around the setting of a biomass power plant which will be designed and analyzed throughout the project especially focusing on performance and feasibility. In order to design this power plant a Spanish location will be firstly selected to set the plant according mainly to the biomass source desired. A specific biomass fuel will be chosen for the study, as well as a plant logistic. The central parts of the study will be on one hand the ORC process design and analysis which will be focused on the selection of the appropriate working fluid and cycle architecture with the objective of enhancing thermodynamic performance and on the other hand the boiler design according to the technologies that will be introduced in the following section in order to obtain its main performance parameters. Finally a feasibility assessment will be build up in order to analyze economic feasibility which is in many cases the main drawback present.

2. BIOMASS POWER PLANTS

Before focusing on biomass combustion for electricity generation, it is important to understand what biomass term is referred to. Biomass has received many definitions but in general terms it refers to the organic matter of animal or vegetal origin and the materials coming from its natural or artificial transformation which have not suffered fossilization processes and which have the potential to be used as a source of energy. Then, fossil fuels such as oil, coal or natural gas are excluded from biomass, as well as the matter derived from them (plastics and most synthetic products), as it takes millions of years to convert biomass into fossil fuels, so these are not renewable within a time-scale mankind can use.

Biomass energy is a renewable energy of solar origin, as it comes direct or indirectly from the photosynthesis process. Sunlight is used by plants through chemical reactions of living cells to capture CO_2 from the air and then convert it into organic matter. In this process, solar energy is being transformed into chemical energy that is collected by different organic compounds.

Burning biomass does not contribute to release new carbon dioxide to the atmosphere because, by replanting harvested biomass, the absorption and return of CO_2 for a cycle of new growth is ensured.

2.1) Biomass situation

This section provides a review in order to understand what is currently the role biomass is playing in the world, focusing later in Spain as country in which the plant to be designed and studied in this project will be set. In this way it is easier to understand the background of this field.

2.1.1) Biomass situation worldwide

According to the International Energy Agency, bioenergy is currently contributing to a 10% of the world primary energy supply, being the largest renewable energy source. Most of it is consumed for basic energy such as cooking and space heating by developing countries, but using very inefficient devices (open fires or simple cook stoves) that often cause adverse impacts on health and environment. On the contrary, modern bioenergy supply results small although growing regularly in the last decade highlighting the use of biomass for heating in buildings and industry (pulp, paper, food processing…). With respect to the bioenergy electricity generation, in year 2014, biomass and waste produced 446 TWh of the world electricity production, which accounts for only a 2% of it. Figure 3 shows global bioenergy power generation and forecast by region according to the IEA Medium-Term Renewable Energy Market

Report on 2015, Paris, where it can be appreciated that OECD Europe leads bioenergy power generation followed by OECD Americas and China.

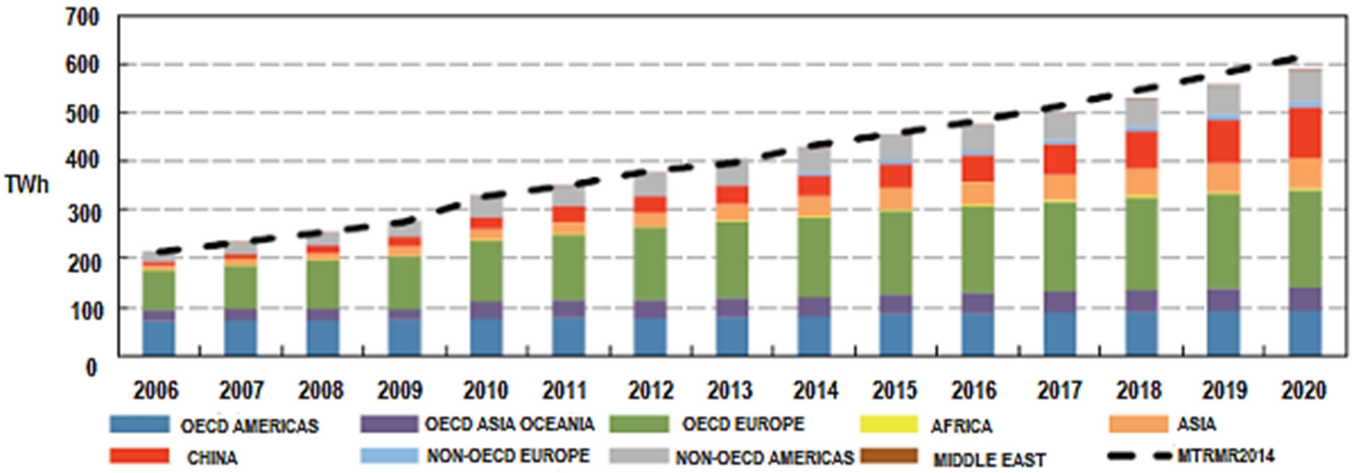


Figure 3: Bioenergy power generation and forecast by region

There exist multiple bioenergy technologies to produce heat and power: solid biomass heating installations, biogas digesters or large-scale biomass gasification plants among others, while coal-fired power plants co-firing biomass appears also as an important option to achieve short-term emission reduction.

Energy production from biomass is not competitive in many cases, so there is a need for economic incentives so that the differences in cost between electricity and heat generated by fossil fuels and bioenergy can be compensated, and it can only be achieved by a strong policy framework. The reasons that support this back up are the advantages of bioenergy over fossil fuels utilization that are related to greenhouse gases reduction, energy security as well as socio-economic development.

2.1.2) Biomass situation in Spain

Biomass is increasing its presence in Spain and it is believed to continue rising in the following years. According to [7], the increase in this type of installations in last years has been remarkable, for example from 2014 to 2015, there has been an increase of more than 20% in terms of number of installations and installed power. Spain has an important potential for biomass utilization, being the third country in Europe generating all types of biomass with 160.036 biomass installations in 2015 accounting for 7.276.992 kW.

But it is necessary to further develop the use of this resource in order to take advantage of waste materials coming from countryside, woods, industries or landfills. This would benefit economy in the country by job generation, environmental impact reduction and fossil fuel dependence decline.

2.2) Advantages and disadvantages

Biomass current situation suggests necessity for further development in the use of this renewable source as its potential seems to be missed. For this reason a more detailed description of advantages and disadvantages that it brings has been provided in this section, trying to sum up its main pluses without forgetting prime contras.

2.2.1) Advantages

- **Renewable source**
  By the time organic matter is being used to produce energy, equivalent amounts are being generated.
- **CO_2 neutral**
  It forms a cycle in which there exists equilibrium between the amount of CO_2 that is released to the atmosphere through combustion and the amount captured by plants to perform photosynthesis.

Figure 4: Biomass cycle, closed carbon cycle [8]

- **Economical**
  It is proved to be 3 times cheaper than fossil fuels.
- **Abundant and distributed worldwide**
  No need for big transport infrastructures.
- **Independent on weather conditions**
  Unlike other renewable energies such as solar, wind or hydro which depend on sun, wind or water conditions, so less intermittency of production and higher reliability.
- **Fuels generated from biomass have a high variety of uses**
  Biofuels could become an alternative fuel to gasoline in transport.
- **Reduces external fuel dependence**

According to Eurostat, Spanish dependence on fossil fuels for year 2015 was 98%, so biomass appears as an interesting option to reduce this too high value.

- **Socio-economic development of rural areas**
  Increased activity and job vacancies.
- **Other advantages related to field management**
  The implementation of energy crops is useful to take advantage of abandoned lands and to avoid soil erosion and degradation. It contributes to wood management and risk of fire reduction and it also reduces environment contamination as it benefits from organic waste to produce energy.
- **Products released are biodegradable**

2.2.2) Disadvantages

- **Previous drying needed**
  Biomass is usually characterized by high humidity content.
- **Lower performance than fossil fuels**
- **It requires many space**
  In order to obtain significant amounts of heat from its combustion, high volumes of biomass are need so big areas are necessary for the different processes aimed to energy production and especially for transport and storage, so difficulties can arise in this aspect.
- **Lower boiler efficiency**
  Boilers used for either liquid or gaseous fossil fuels have higher efficiency.
- **Higher investment levels**
  Mainly because of the boiler which is bigger and more complex due to fuel injection and ashes removal systems. In addition, there are higher operation and maintenance costs.
- **Environmental aspects**
  Bad use of biomass could promote forest deforestation and natural habitats destruction.
- **Emissions**
  Methane gases are often emitted, damaging Earth's ozone layer and although direct emissions are supposed to be neutral, it has important direct emissions coming from some biomass pretreatment processes and transportation.

As it can be noted from this section, main disadvantages have to do with economics, which is one of the reasons for its reduced development with respect to other technologies supporting what it was stated in previous section, stronger back up is required in order to achieve a further development.

2.3) Biomass as energy source

In this section there will be a further approach to the main topic of this project, power generation from biomass source. It has been tried to provide a general overview of biomass as energy source. One of the reasons is to get the criteria to select an appropriate biomass fuel in order to know which properties we may look for and the reasons for it. It also includes a review of the different ways there exist in order to transform biomass into energy to make clear where this project will focus and the principal alternatives there exist.

Biomass as an energy source can be classified by its origin into natural biomass, residual biomass or biomass coming from energy crops. This includes products or wastes coming from agricultural activities (either of vegetal or animal origin) or forestry activities and their related industries, as well as the biodegradable fraction of industrial and municipal waste.

Main solid fuels obtained from biomass in Spain are olive stones, grape or olive pomace, shells from dried fruits and nuts as well as products or wastes from our forests, such as wood, barks, thistles, splinters, straw or pellets [9].

For the processing as an energy source, the main material properties of interest are related to [10]:

- **Moisture content**
  While thermal conversion requires low moisture content feedstock (typically <50%) bio-conversion can use high moisture content one. If high moisture content is used in thermal conversion the energy balance of the process is impacted negatively as the LHV is reduced.

- **Calorific value**
  Calorific value is an expression of energy content released when burnt with air. The actual amount of energy recovered will vary depending in the conversion technology and the state of that energy (combustible gas, oil, steam…). Biomass LHV is around 16 MJ/kg [11]. This value is closer to that of coal which is around 23 MJ/kg, but compared with that of other fossil fuels such as oil or NG, which have a LHV around 42 and 47 MJ/kg [11] respectively, it is quite low.

- **Proportion of fixed carbon and volatile matter**
  The volatiles content (VM) of a solid fuel is the portion of it banished as a gas (including moisture) by heating (to 950ºC for 7 min), while the fixed carbon content (FC) is the mass that remains after the release of volatile matter, excluding the ash and moisture content. VM and FC contents provide a

measure of the ease with which the biomass can be ignited and then gasified or oxidized, that depends on how biomass is utilized as energy source.

	C *(%)*	***H*** *(%)*	***O*** *(%)*	***N*** *(%)*	***S*** *(%)*	***Ash*** *(%)*	***LHV*** *(MJ/kg)*
Corn	42.1	6.5	48.9	1.2	0.1	1.5	17
Straw (wheat)	43.4	6	44.5	0.8	0.1	7.7	18
Bark	47.8	5.9	45.4	0.4	0.1	1.5	19
Hardwood	48.3	6	45.1	0.2	0	0.4	19
Coal (lignite)	58.8	4.2	13.6	0.9	0.5	22	22

Table 1: LHV and composition of some biomass solid fuels in contrast with Coal [12]

Comparison of biofuels with coal, represented in Table 1, shows clearly that the higher portion of oxygen and hydrogen, compared with carbon, reduces the energy value of a fuel due to the lower energy contained in carbon-oxygen and carbon-hydrogen bonds, than in carbon-carbon bonds. This can be explained through the Van Krevelen diagram [13] showed in Figure 5. This diagram illustrates the implication of the O:C and H:C ratios on the calorific value of solid fuels. The lower these ratios are the higher heating value of the fuel and then the greater energy content.

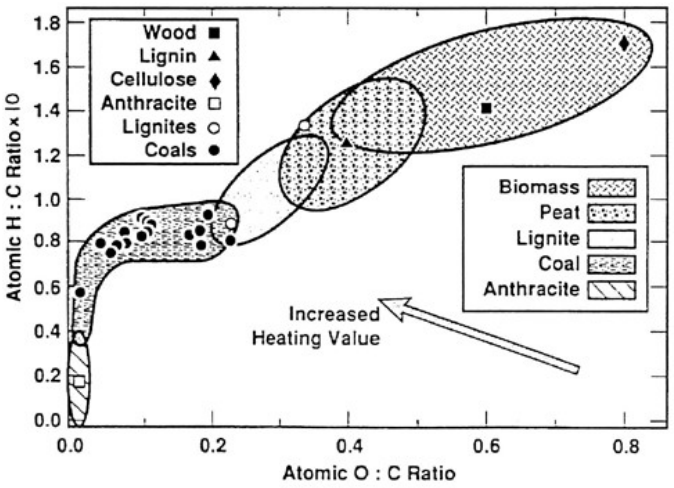


Figure 5: Van Krevelen diagram [13]

- **Ash/residue content**

  The ash constitutes the solid residue produced by the chemical breakdown of a biomass fuel by its combustion with air. Depending on the ash content, the available energy of the fuel is reduced proportionately. Biochemical conversion processes have a higher percentage of solid residues than the ash content formed during the combustion of the same material because solid residue in

biochemical process represents the carbon which cannot be degraded further biologically, but which could be burnt during thermochemical conversion.
The ash content of biomass affects both handling and processing costs of the overall biomass energy conversion cost.

- **Alkali metal content (Na, K, Mg, P and Ca)**
  It is especially important for any thermochemical conversion process as, together with silica which is present in the ash, it produces a sticky and mobile liquid which can block airways of the furnace and boiler plant.

- **Cellulose/lignin ratio**
  These are important only in biochemical conversion processes. Biodegradability is greater for cellulose than for lignin, so plants with greater content in cellulose than lignin are preferred and it constitutes a determining factor when selecting biomass plant species for biochemical processing.

- **Bulk density**
  Volume of biomass materials both produced and processed is another important characteristic. Importance of the produced bulk density comes from transport and storage costs while for processed biomass it impacts on fuel storage requirements, sizing of the materials handling system and the way the material is likely to behave in further thermo-chemical or biological processing.

Among the products in which biomass can be converted we find: electrical/heat energy, transport fuel (these two are related to energy) or chemical feedstock. Energy produced trough biomass can be used for heating and production of hot water in the domestic sector, heat for industrial processes and electricity generation, which is the main goal of this project.

The conversion of biomass into energy can be carried out in multiple ways. The main ones are thermochemical and biochemical process technologies although it can also be found mechanical extraction.

With respect to thermochemical conversion we identify three important processes: combustion, pyrolysis and gasification among others such as liquefaction that are of less interest. Within biochemical conversion we find two processes available: digestion, which produces biogas which consists on a mixture of methane and CO_2, and fermentation to produce ethanol. Although this project is focused on biomass combustion, a brief overview of the main energy conversion technologies has been included to provide general framework information based on [14] and [15] sources.

2.3.1) Thermochemical conversion

a. Combustion

It consists on burning biomass with air to convert into heat the chemical energy contained in biomass. Biomass combustion produces hot gases at temperatures around 800-1000ºC. This heat can be directly used or converted into mechanical power or electricity. As previously commented it is possible to burn any type of biomass but the one with high moisture content is better suited for biological conversion, as for combustion it will be feasible only for moisture content <50% or after biomass pre-drying.

For combustion plants the scale ranges from very small to large scale and the net bio-energy conversion efficiency we can find in conventional biomass power plants ranges from 20 to 40% with the higher efficiencies obtained for plants with more than 100 MWe or for co-combustion in coal-fired power plants.

b. Gasification

It consists on converting biomass into a combustible gas mixture by partial oxidation at high temperatures (800-900ºC) and 10-50% oxygen. The gas produced has a low calorific value and it can be used as fuel for gas engines and turbines or can be directly burnt. The product gas can be used as feedstock (syngas) in the production of chemicals such as methanol and hydrogen, which can be useful for transportation.

c. Pyrolysis

It consists on the conversion of biomass to liquid and gaseous products, leaving also a solid residue richer in carbon content (char), by heating biomass at temperatures around 500ºC in the absence of oxygen. It is used mainly to produce bio-oil which can be used in engines and turbines or as feedstock for refineries.

Figure 6 summarizes the main processes, intermediate energy carriers and final energy products resulting from thermochemical conversion.

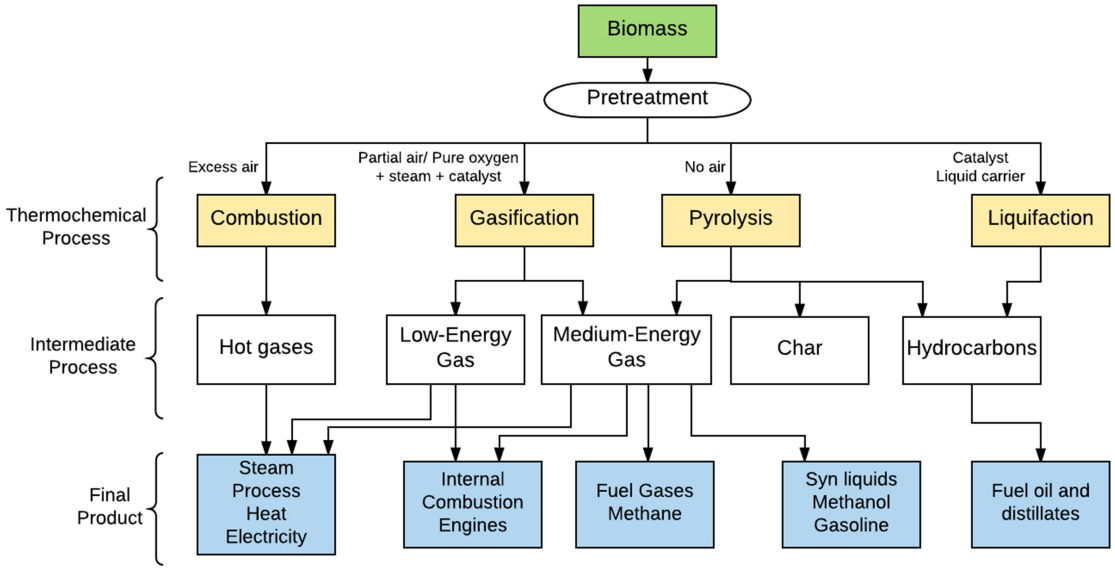


Figure 6: Biomass thermochemical conversion processes [14]

2.3.2) Biochemical conversion

a. Fermentation

It consists on breaking down the glucose or carbohydrate of plants converting it into an acid or alcohol. Yeast or bacteria are added to the biomass material to feed on sugars producing in this way ethanol and CO_2. Then the ethanol is distilled (energy intensive process) and dehydrated to obtain higher alcohol concentration that achieves the purity required for automotive fuel. It also leaves a solid residue that can be used as cattle-feed and in the case of sugar cane; the bagasse can be used as a fuel for boilers or for subsequent gasification.

b. Anaerobic digestion

It is a process in which the biomass is converted by bacteria in an anaerobic environment into a gas, mainly composed by methane and CO_2 with small quantities of other gases such as hydrogen sulphide, and which is known as biogas. This technology is extensively used to treat high moisture content organic wastes (>80% moisture). Biogas can be used directly in spark ignition gas engines and gas turbines, or upgraded to higher quality by removing CO_2. Overall conversion efficiency from biomass to electricity is around 10-16%.

2.4) Biomass storage, pretreatment and transportation

These processes constitute an important factor of biomass power plants as they strongly impact costs, complexity and project viability. For this reason it is important to discuss and understand the main options present in terms of biomass preparation and transportation. This section is focused in biomass combustion, setting aside other conversion ways in order to focus our attention in the main goal of the project.

2.4.1) Biomass Storage

Biomass storage in plant proximities has two objectives. The main one is to ensure supply for certain, generally short, period. In this way, possible biomass supply fluctuations are being absorbed so that they do not affect plant operability. Another objective could be natural drying enhancement by evaporation of the water contained in biomass.

Among the different types of warehouses it can be found [16]:

- Outdoor storage: without any protection against weather conditions, which may increase biomass moisture content in determined times of the year (winter and rainy seasons). In addition, the floor must be waterproof in most cases to avoid soil contamination.
- Closed ship: It is one of the best options as it avoids the risk present in the outdoor storage and, if there is adequate ventilation, it enhances natural drying. The main disadvantage here is the risk of deflagration which is favored by the dusty atmosphere.
- Roofed but open ship: the best option in the sense it is a compromise solution to both previous problems, as, although rain does not fall upon biomass directly, humidity does. Natural dried is favored in summer and dried periods but not in winter or humid seasons.
- Tanks and silos: most common option for sawdust.

The main criteria that must be considered when selecting the proper warehouse are [16]:

- Type of biomass
- Biomass granulometry
- Initial moisture content
- Amount of biomass considered necessary to keep in stock to absorb the fluctuations in biomass supply that could arise throughout the year.
- Site soil conditions to avoid leachates infiltrations.

- Weather conditions, especially in terms of average humidity, total rainfall, rainfall distribution throughout the year and average, minimum and maximum wind speed and temperature.
- Maximum height of the piles. Parameter related to deflagration possibilities, available space and necessary amount of biomass to be kept in stock. To avoid deflagration, maximum temperature inside piles of biomass materials must be controlled and kept below 120ºC, although the ideal situation would be below 80ºC. From 120ºC on, it experiments a quick increase until 180ºC, when auto ignition occurs.

For this project it will be looked for optimum ways of storage but taking into account concerns about feasibility so that closed ships are preferred in order to reduce pretreatment processes regarding humidity content.

2.4.2) Pretreatment Processes

The ideal situation would be that biomass could be introduced in the boiler without the necessity of previous treatments, but this is not always possible as combustion equipment tend to require of some biomass physical conditions, especially in terms of moisture content and granulometry. Each additional process means more equipment, higher inversion costs and increased complexity of operation and maintenance, but it becomes necessary in many cases due to boiler conditioners and because this earlier preparation process enhances and eases reaction process between fuel and oxidizer.

Among pretreatment objectives it can be found:

- Making biomass enter in the boiler homogeneously, so that the boiler has a constant and similar energy flux.
- Reducing its granulometry to increase its specific surface. The smaller the grains are the bigger surface available for the fuel and oxidizer to react, so the reaction is accelerated and unburnt biomass is reduced.
- Diminishing moisture content, avoiding in this way that part of the heat released in the combustion is used for water vaporization, reducing flue gases temperature.

Among the most common pretreatment processes it can be found [16]:

i. Drying
   Among the consequences of high moisture content, we find:

- Thermodynamic consequences: LHV is remarkably reduced, decreasing combustion efficiency. Figure 7 shows the impact of moisture content on the calorific value.

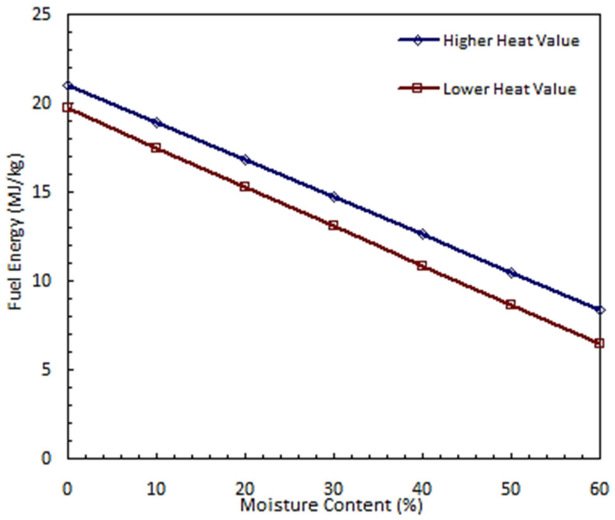


Figure 7: HHV and the LHV for a wood fuel as moisture content increases

- Mechanical consequences: it can cause blockage and problems in transportation preventing it from its regular circulation.
- Chemical consequences: water contained can hinder combustion process reason why some combustion technologies have very strict limits in moisture content.

Drying processes can be carried out in several ways: **natural drying**, that results favored in high temperature and low humidity zones, **forced drying applying cold dry air**, with the possibility of simply allowing the air from the exterior to enter the ship and **forced drying applying heat**, which is the most common and effective way but with the difficulty of finding a heat source at good price.

In case of going for a forced drying applying an external source of heat the best options to avoid using fossil fuels are: using an auxiliary biomass boiler to burn very low-cost biomass or using the hot flue gases leaving the main combustion and putting them in direct or indirect contact with biomass to be dried to evaporate the water contained in biomass.

ii. Chipping

In case of using lignocellulosic wood, it is usually received larger than the optimum size for combustion, so it must be splintered.

iii. Milling
The objective of milling is to reduce even more the biomass size to increase its specific surface. It tends to be a boiler demand, but it must be avoided if possible as it means and additional process and then increased costs.

iv. Sieving
Some plants require strict granulometry controls to ensure correct combustion, so before and after grinding process, the material is passed through sieves of different sized to ensure that only the material capable of passing through them goes to the next process. These sieves tend to be subjected to some movement to ensure material moves from entrance to exit; commonly they are tilted and subjected to intense vibrations.

v. Pellets
Pellets consist on small cylinders composed of materials coming from woody residues and that have been previously crushed and dried to remove moisture content. Later it is compacted and cut up, obtaining a homogeneous fuel in terms of composition. Pellets are characterized by its low moisture content (<15%), important volume reduction (1/5), better storage capacity, high density (600-700 kg/m^3), excellent heat capacity and durability and better dosage capacity.

The more pretreated biomass is, more heat it could be generated from it but when selecting pretreatment necessary it must be taken into account it must be selected in a compromise with feasibility.

2.4.3) Transportation to the boiler

Main ways we could choose for the transportation are listed in this section:

- Loader.
  It moves big amounts of biomass from the trucks discharge zone to temporal storage zone and sometimes to the transportation system that will lead it to the pretreatment processes.
- Endless or Archimedean screw.
  Widely used for medium-low granulometry solids.
- Conveyer belt.
  Usually made of rubber. It must be considered that in case of working with fine granulometry it is convenient to cover the belt to protect it from wind.
- Bridge crane.

Used when the particle size is big enough. It can be automatic or manually controlled to take biomass from different points in the warehouse.

- Robotic systems.
  It requires biomass shape homogeneity. This system can perform all the tasks from the discharge from trucks to the boiler feeding without operator's interference.
- Pneumatic conveyor.
  Used for very fine granulometry. It consists on moving the products through various tubes via air pressure, allowing for extra vertical versatility.

In many cases in a unique plant there exist several of the described systems. For the case study biomass power plant, transportation mechanism will be selected according to granulometry and plant configuration.

2.5) Electrical generation from biomass combustion

Now that a general overview of biomass utilization, features and processes, has been provided, this project will focus on biomass combustion, which is the technology this project deals with as previously introduced. This section describes the conventional process to transform biomass into electricity by biomass combustion. It also provides a review of the most common types of boilers we can find in these plants, comparing them to give some criteria that finally will result useful as it will lead to choose the optimum one for the plant to be designed. Boiler plays a vital role in the process strongly impacting performance and economics of the plant, so right selection is crucial.

2.5.1) Rankine Cycle

Biomass thermoelectric power plants generate electricity taking advantage of the chemical energy contained in a specific amount of biomass. This chemical energy is released as thermal energy by means of a combustion process. To produce this heat into electricity it is used a thermodynamic cycle, being water the most commonly used working fluid. Figure 8 presents the scheme of the conventional cycle used, the classical Rankine Cycle.

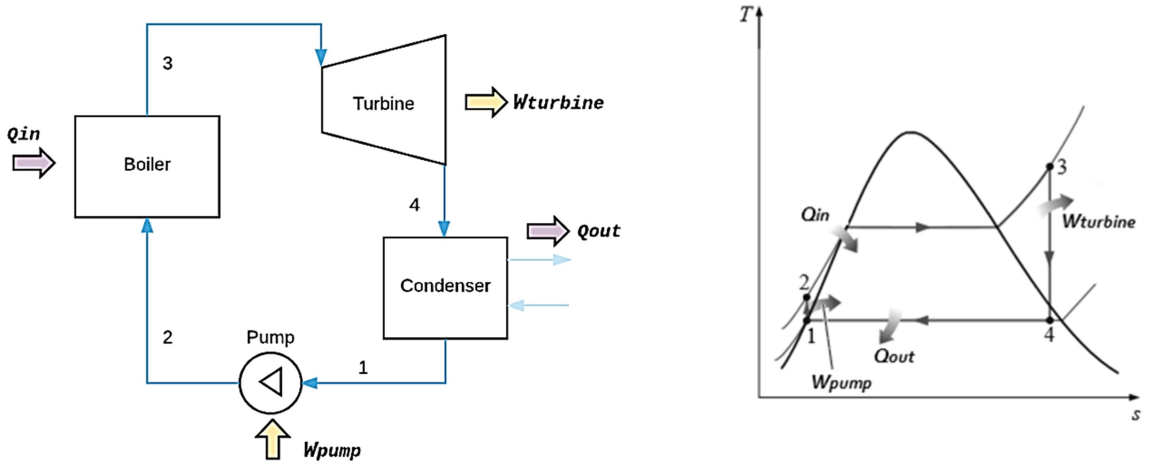


Figure 8: Simple Rankine Cycle scheme (left) and T-s diagram[34] **(right)**

In the Rankine Cycle, four processes can be distinguished [17]:

- **Process 1-2:** Isentropic compression in the feed pump to increase the pressure of the working fluid (in liquid phase) from the condensing pressure to the steam generator pressure. This process implies power consumption.
- **Process 2-3:** Isobaric heat transfer in the boiler. Liquid going out of the feed pump at high pressure enters the boiler and is heated until saturation temperature. Then by further energy addition fluid is evaporated and converted to saturated steam.
- **Process 3-4:** Isentropic expansion in the turbine from maximum pressure to the condensing pressure. This expansion produces the work which will be converted to electricity by the generator. The expansion is always limited by the temperature of the cooling medium and by the turbine blades erosion. The formation of water droplets can damage the turbine blades as the process moves further in the two-phase region so vapor at turbine exit requires qualities above 90% to avoid this risk.
- **Process 4-1:** Isobaric heat rejection in the condenser where the mixture of vapor and liquid leaving the turbine is condensed at low pressure, usually using water as the cooling medium. In well-designed condensers vapor pressure is quite below atmospheric to approach saturation pressure of the working fluid at the cooling water temperature.

In this process, thermal energy released in the biomass combustion process is captured by the tubular beams, heating a specific mass flow of the working fluid, in this way it is achieved superheated vapor at high pressure and medium temperature (in these plants the typical maximum temperature reached is lower than in other

plants being below 470ºC to avoid condensation of chlorine present in biomass). This one is expanded in the turbine producing rotating mechanical energy that will be transformed into electrical by the generator.

2.5.2) Biomass combustion boiler

Boiler constitutes the central element and main concern in a biomass thermoelectric plant as it is the component in which chemical energy is transformed into thermal.

Boiler tends to be the component that leads to more potential problems (provoking most of the halts) requiring strict maintenance. The main reasons are: first, biomass combustion is an emerging technology, not so developed as other combustion processes (such as coal combustion), second, the high content in potassium and chlorine causes corrosion in the boiler and third, the combustion is not very stable as it presents important variations in terms of pressure and temperature, and conditions at the entrance of the boiler may vary considerably.

For these reasons, the correct selection of the boiler is a key factor that can lead to success in the achievement of a project for electric generation from biomass while the wrong selection will lead to difficulties to monetize inversion costs.

Among the different types of boilers, we find:

i. Depending on fluids circulation [16], [18]:

- **Fire tube boiler**

  In these boilers, hot flue gases pass through tubes while water do it outside them, which makes them to have lower rate of steam generation. These types of boilers are low-medium pressure boilers as its limit is around 25 bars, which make them to have lower overall efficiencies (≈75%). For these reasons fire tube boilers are not used for large power plants but for small scale ones. They are easier and cheaper to operate although they require more floor surface and result difficult to transport.

- **Water tube boiler**

  Contrary to the fire tube boilers now water flows through tubes while hot flue gases do it around them through the shell. They have higher steam generation rate and they are considered high pressure boilers as they are suitable to operate between 25-165 bars reaching even higher pressures in super critical boilers. They have higher overall efficiencies, up to 90% with

an economizer and they require less floor space. Water tube boilers are more complex to construct and more expensive to maintain, although their transportation result easier as its parts can be separated.

Biomass plants tend to use fire tube boilers as water tube ones require conditions and materials that make them unfeasible in biomass plants, especially low-scale ones, so following this trend the plant designed in this project will also use a fire tube boiler although it means efficiency losses.

ii. Depending on the combustion type [16], [19]

- **Grate furnace**

Its working principle is based on fuel progress through the boiler by means of pulling elements provided with movement among them. These movements allow the materials to flip and get totally burned while it allows wastes to fall to the bottom. Elements composing the grate hold the fuel and insufflate the air necessary for combustion among them.

The combustion process goes over four clearly differentiated stages:

- Drying process: When biomass enters the furnace, it is heated by preheated air, irradiating heat from walls and combustion gases, and humidity is removed in a temperature range of 50-100ºC.
- Volatilization: Fuel organic matter suffers a thermal decomposition generating some volatile components. This process occurs in a wide temperature range of 200-750ºC although main release occurs at 425-550ºC.
- Volatile matter combustion: They are burned immediately as boiler temperature 700-1000ºC is quite higher than volatile matter ignition. High temperature is wanted to have complete combustion of gases and it is required excess of air to avoid having unburnt compounds and turbulence to enhance fuel and oxidizer mix. Gases residence time in the boiler is around 2-4 seconds.
- Combustion of charcoal solid residue: After previous stages occur, the remaining biomass material is still composed of carbon and inert incombustible matter. Charcoal residue keeps burning in the grate for 5-10 minutes.

Grates can be travelling, reciprocating or vibrating type.

- **Fluidized bed**

It consists on suspending solid fuel particles, ashes and inert matter on upward-blowing jets of air during combustion process.

Only 2-3% of the bed is carbonaceous, the rest is inert matter that provides a large heat store, which absorbs possible fluctuations in vapor generation caused by fluctuations in fuel calorific value that come from moisture and fuel composition variations.

SO_2 emissions produced in biomass combustion are generally quite low, but when sulfur content of the fuel is high it is captured inside the boiler by the sorbent (limestone) producing sulfates extracted from the boiler together with the ashes instead of doing it with the flue gases. Cyclone separators are used to remove particulate matter from flue gases.

We find two types of fluidized beds depending on the degree of fluidization (fluidization velocity) and it will be selected depending on the fuel calorific value and size of installation. These two types are:

- Bubbling-bed technology
  It uses low air velocities, most part of the solids remain in the bed and only less than 10% move on to the cyclone. Due to the higher inertia present in the combustion chamber, its use is oriented to fuels with higher contents of volatile ashes and/or higher moisture content. Among its main advantages we find: lower combustion temperature, good heat transfer and avoid other contaminating gases such as halogens.
- Circulating fluidized bed technology.
  With high air flows that enter and move the bed material it is possible to recirculate nearly all the bed material with adjacent high volume, hot cyclone separators. It is more complex regarding operation but it achieves a better SO_2 capture and then less limestone requirement. In addition, temperature is kept constant throughout the cycle, we have fewer losses in the fireplace and NOx emissions are lower.

If we compare grate firing and fluidized bed technology, which are represented in Figure 9:

Using grate firing in the fireplace has some advantages:

- Widely tested technology with multiple references in the market
- It admits heterogeneous fuels with great variations in fuel granulometry
- Insensitive to possible agglomerations in the fuel bed
- Low dust presence in flue gases

- Lower cost

In comparison with grate firing, the advantages of fluidized bed technology are:

- Higher performances due to lower corrosion
- Easy operation: quick combustion process means low inertia in the furnace and then short periods of start-up and halt
- Easy to control
- Easy maintenance: lower size than grate firing furnace for the same capacities
- Unburnt biomass can be cooled down and separated from the inert matter
- It admits fuels with wider LHV range and it offers the possibility to mix them.
- Higher quality of flue gases due to the possibility to use corrective additives in the bed.
- It admits a high moisture content variation in the fuel.
- Better burnout of fly ash

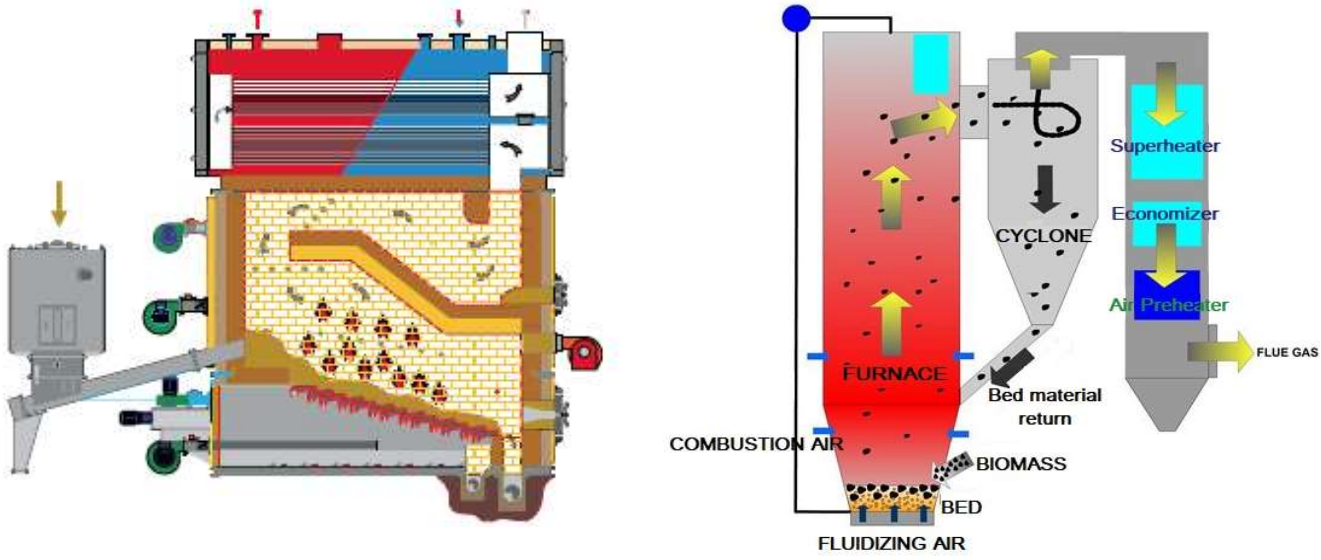


Figure 9: Grate firing (left)[16] **and circulating fluidized bed boiler (right)** [48]

Although fluidized bed may appear as a better technology, the reality is that for a small scale power plant as the project case, fluidized bed boiler would result more complex due to bed agglomeration problems related to high content of biomass in alkali metals. High contents of sulphur from combustion together with the chlorine and phosphorus from the fuel generate eutectics, which are low melting compounds which deposit on bed particles coating them as a tacky ash layer. These agglomerates obstruct good mixing and provoke hot spots. This problem, which in many occasions can lead to plant shutdown, is not so evident in grate-fired boilers where lower potassium release is

showed as its ash is mostly bottom type contrary to fluidized bed which has fly ash [20]. For this and other reasons regarding biomass size, fluidized bed technology requires increased fuel pretreatment and preparation, which as explained in previous sections has an impact in biomass acquisition cost.

As plant being designed is a small scale one, to reduce complexity in the operation, avoid increased boiler wear and the higher costs it implies, grate firing technology seems to the appropriate for this project. According to [21], which provides a comparison between this two technologies, modern grate-firing systems are preferred for conversion from energy to biomass and are the most suitable technology for CHP production. Grate firing technology used for the plant of this project will be presented further on, in boiler design section, more in detail.

2.6) Plant location

For the power plant design, an appropriate location is will be selected in this section as it is the first approximation for power plant design.

When selecting the location of the plant, the main aspects to consider will be:

- ✓ Proximity to biomass resource. It is one of the main points as the closer the plant is to the raw material it is going to burn, the lower will be the transportation costs, thus reducing at the same time indirect CO_2 emissions caused by transport.
- ✓ The proximity to communication lines. Good access to roads to ease and make cheaper transportation of raw materials as well as personnel.
- ✓ Proximity to electric lines for both consuming the electricity that the plant requires from the grid and to transfer the electricity generated in the plant.
- ✓ Proximity to rivers to use its water for cooling.
- ✓ The area of the location selected must, not only be as large as necessary, but also with an optimum topography, as the flatter it is, the easier and cheaper will be the plant construction.
- ✓ We must consider other aspects that could be negative, such as the proximity to urban areas, due to noise and pollution produced by the plant itself and by the biomass transport or the proximity to protected areas to avoid any possible contamination of these zones.
- ✓ We must also avoid constructing the plant near existing ones.

According to Agenex, the Energy Agency of Extremadura, this community is the 5th Spanish region with highest biomass potential, which accounted for 6,8 million tons of biomass per year accounting for existing remains from forest exploitation, remains

from agricultural activities, existing masses that have not been exploited and land available for energy crops. At the beginning of 2017 more data have been published and it reveals that the region could produce up to 4 million tons of biomass per year only by forestry matter. But according to Agenex only 3% is used as fuel. This information results a motivation for this project and for this reason it is going to be studied the placement of the Biomass-ORC power plant in one of its municipalities, Badajoz.

In order to identify the biomass resource in a determined region it is going to be used an online tool for biomass calculation called BIONLINE [22], which evaluates biomass potential in Spain with respect to its different origins. It quantifies biomass from forestry and agricultural origin (remains from forest exploitation and agricultural crops and biomass coming from masses susceptible of implantation in both agricultural and forestry land) and it was elaborated from methodologies schemes and data selected by experts in forestry and agricultural areas.

For Badajoz, the remains from forest exploitation and forestry land susceptible for energy crops are showed in Figure 10 and Figure 11 respectively in tons per hectare per year. In this way, optimum locations regarding proximity with biomass source are easy to identify.

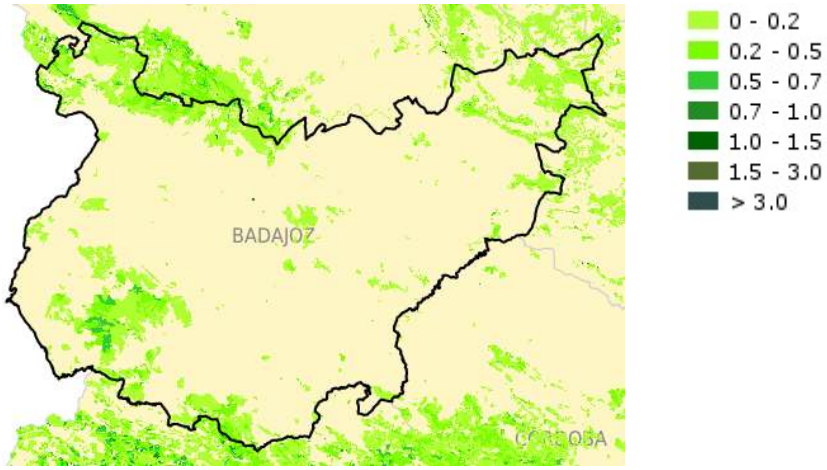


Figure 10: Remains from forest exploitation (t/hayear)[22]

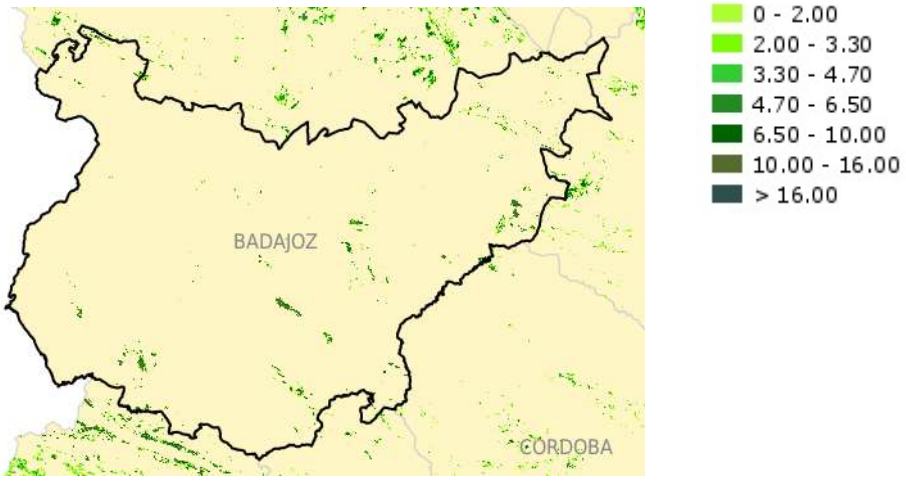


Figure 11: Forestry land susceptible for energy crops (t/hayear)[22]

It has been selected the best suited zones, pointed with a red circle in Figure 12 by combining both biomass zones of interest for this project.

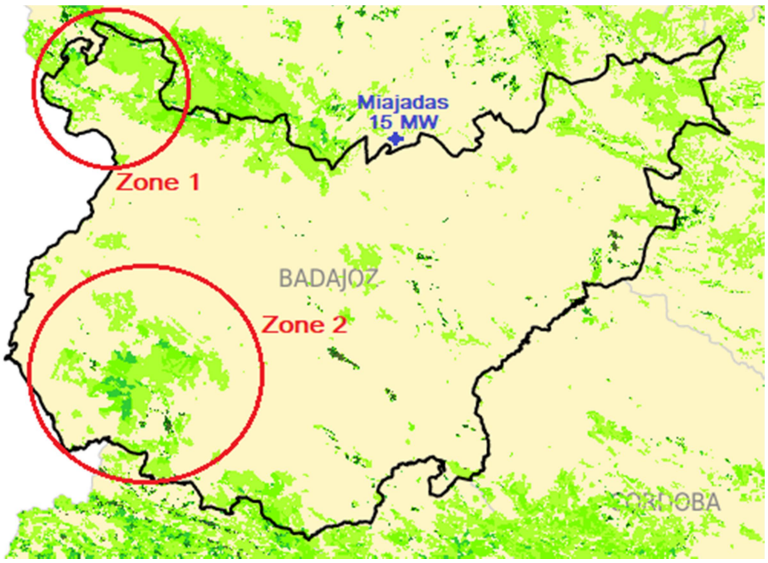


Figure 12: Best suited zones selection and potential competitor[22]

One of the aspects to consider was not to construct near already existing plants. It has been just considered potential biomass power plants in the proximities that could mean a reduction in the available mass to exploit. The one we have identified as necessary to take into account is Miajadas Biomass Power Plant which has 15MW power and that uses mixed biomass from both herbaceous and woody origin. This plant location is pointed out in Figure 12 and as it can be appreciated it does not bring any risk regarding proximity to the selected areas.

By looking at the map from REE grid for the selected areas shown in Figure 13, it can be appreciated that Zone 1, is worse-suited than Zone 2 regarding proximity to transmission lines as they are located too far and this would increase costs and complexity. On the contrary, Zone 2 looks well-suited due to its proximity to high voltage lines that are highlighted in red (400kV) and green (220 kV).

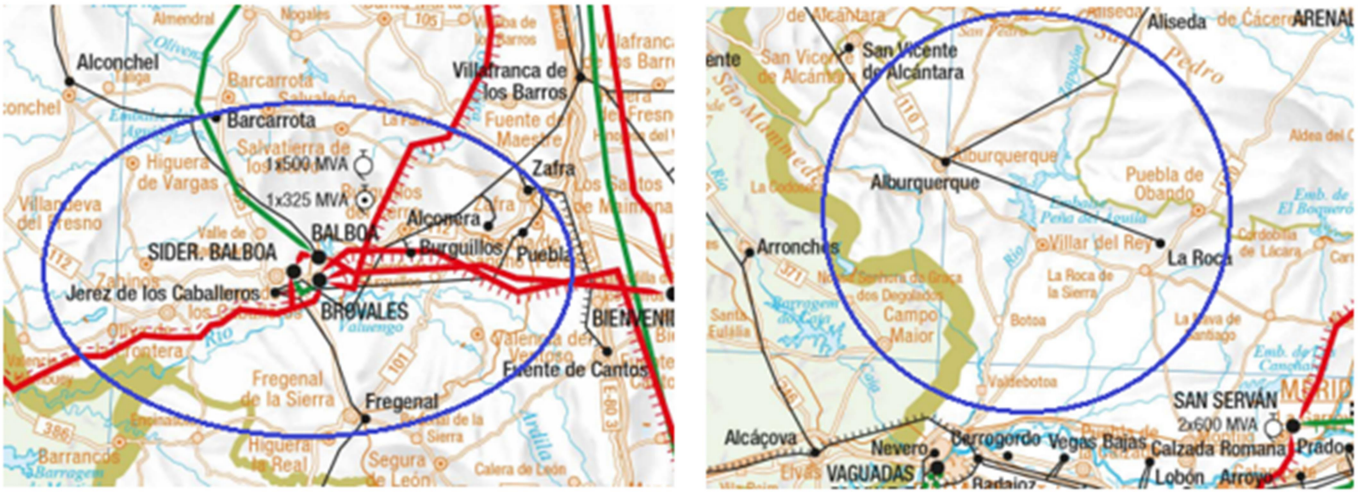


Figure 13: REE transmission lines map for Zone 2 (left) and Zone 1 (right) [49]

With respect to the proximity to communication lines, study zones have been identified in the road map. As it can be seen in Figure 14, Zone 2 is again preferred as it is better communicated.

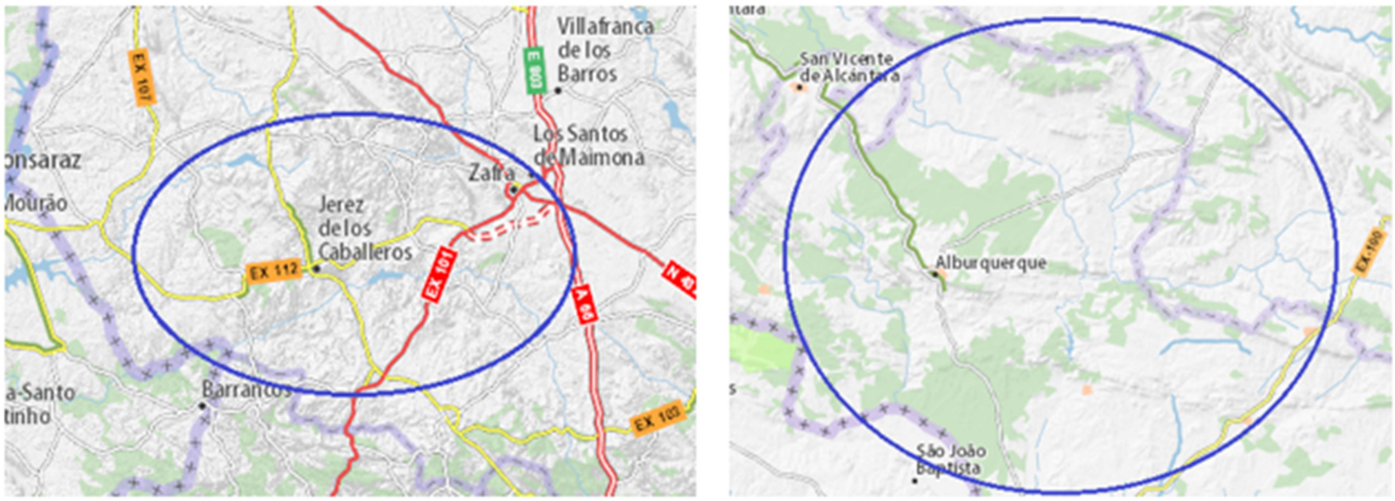


Figure 14: Road map for Zone 2 (left) and Zone 1 (right) [50]

So, considering proximity to communication and electric lines as key parameters, Zone 1 is going to be rejected as it will suppose remarkable increased costs with respect to Zone 2. So now, focused on Zone 2 other parameters must be analyzed.

We are going to point out the urban areas we need to consider in order to try to place the plant sufficiently far from them in order to avoid disturbances to their populations. These areas have been pointed out in yellow in Figure 15.

To reduce the areas of interest, now we must consider the remaining parameters commented at the beginning: proximity to rivers in order to ease cooling of our plant, as well as selecting a level ground. Combining these two factors we still can find several zones of interest, but taking into account the better location with respect to transmission and communication lines, it has been selected the final location pointed out in red in Figure 15 and Figure 16.

Figure 15: Urban areas to consider in Zone 1 (yellow) and final location (red) [51]

Figure 16, shows three main aspects that make this to be an optimum location. Red line represents a high voltage transmission line (400kV), green lines represent communication lines, being road EX-112 the most important one and blue lines represent a source of water for cooling. The closer urban area is Burguillos del Cerro, which is located at 3.6 km.

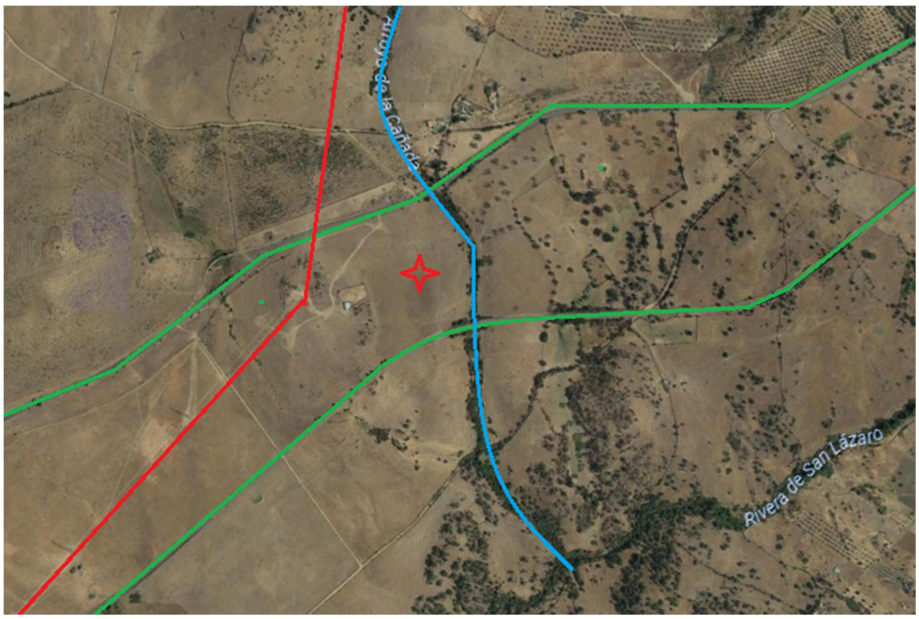


Figure 16: Final location overview [51]

2.7) Fuel and plant logistic selection

Now that the location has been selected and grate furnace has been the burning technology chosen, biomass fuel is going to be set, as it is an important parameter that will affect performance and feasibility.

In previous section we had decided the optimum location mainly because of its proximity to biomass resource based on forest exploitation and forestry land susceptible for energy crops. In this way we had already reduced the fuel possibilities as we were just taking into account biomass from forest origin, dismissing in this way biomass from agricultural and urban waste origin. Biomass from agricultural origin is considered as one of the cheapest and most widespread biomass source, but it requires much more space for transportation and storage which would increase investment costs.

Wood chips can be obtained easily on site and then transported and pretreated with lower space requirements and lower energy requirement for these processes, reducing the costs associated with source transportation.

The woody fuel which will be used will have different origins in order to avoid plant shutdown due to lack of biomass resource. On the one hand, the plant will develop forest energy crops in available zones showed by BIONLINE tool. It will also receive biomass from forestry exploitation residues and finally stem wood from previous thinning for other commercial purposes. As these fuels are from woody origin they will have similar properties. For further calculations and according to the vegetation from

the zone, willow properties will be the ones used, as according to [23], [24], willow constitutes an abundant tree in Badajoz. These properties are presented in Table 2 regarding dry ash free chemical composition, moisture content and net calorific value.

Dry ash free chemical composition for willow (%)	
C	47.1
H	6.1
O	44.2
N	0.54
K	0.26
S	0.045
Cl	0.004

Other properties	
% Humidity	6-15
% Ashes (dry)	2
NCV (MJ/kgK)	18.4

Table 2: Willow properties with percentages representing % weight [7]

This tree presents favorable properties in terms of NCV, which is quite competent for a biomass fuel as we can check in Section 2.3) and also in terms of humidity, as there are other types of biomass that present much higher values, specially agricultural origin ones, so less pretreatment effort is required.

For the logistics of biomass, the process that the plant will follow has been illustrated in Figure 17. Wood from logging residues and forest energy crops will be chipped on site provided that the location makes it possible as this is the recommended trend in literature. Then it will be transported by trucks to the plant location where if it has an acceptable size it will be stored and if it is not it will be chipped because as discussed in pretreatment section a smaller and uniform size results more beneficial. As the boiler selected is not too restrictive in terms of granulometry and size, milling and sieving or pellet production is not performed as it would increase costs and complexity and may not result economically worthy for the study case.

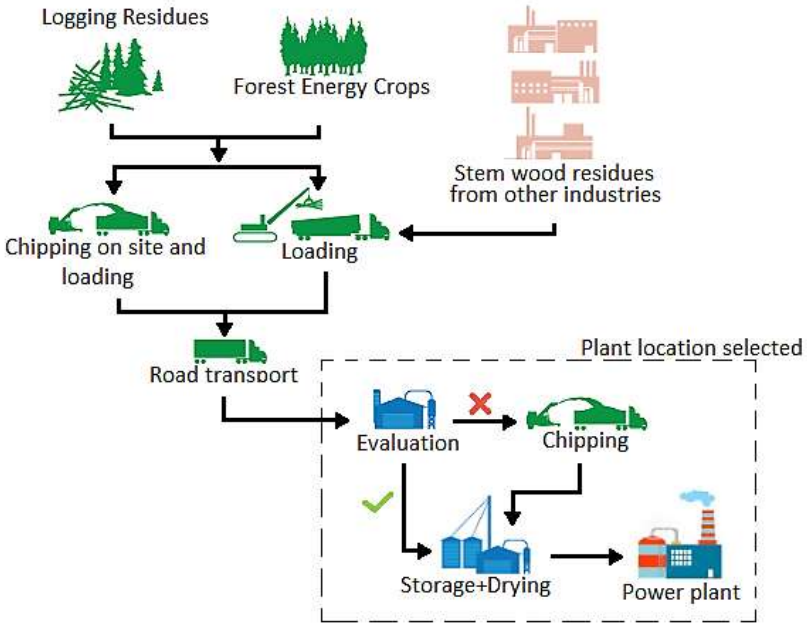


Figure 17: Biomass plant logistic for the study case

With respect to drying the method used it will be natural drying on storage site. The storage will be a closed ship in order to avoid problems arising from meteorological conditions such as rain, wind and humidity that could affect the process. For drying it will be allowed air from the exterior to enter the ship as humidity content of the fuel chosen is not so high so there is no need for more effective methods that will considerably increase the cost. Special attention will be needed in order to avoid biomass auto ignition. With respect to the transportation to the boiler, it will be performed through a conveyor belt as wood chips present an appropriate granulometry for it.

Next chapters will be focused on the ORC designed, as it is one of the key aspects for the project. After it, the project will come back to the boiler to provide a more detailed design according to the requirements of the ORC.

3. ORGANIC RANKINE CYCLES

Before skipping to next section in which ORC design will be developed, it is important to analyze ORC technology to understand the main advantages and disadvantages that lead to use it instead of implementing a conventional steam rankine cycle, its functioning, the alternatives there exist with respect to its use and its application for biomass technology. A description of the criteria that must be followed in next chapter when selecting an appropriate working fluid has been already introduced in this chapter and finally market evolution and manufacturers' information has been recorded for a complete inquiry of this technology and to examine current development trends.

Organic Rankine Cycles are conceptually like conventional steam Rankine Cycles in terms of layout and components, the main difference is the working fluid, which instead of water consists on an organic medium.

The main interest in ORCs is its ability to recover low-grade heat, which is very convenient to implement decentralized lower-capacity power plants.

3.1) Advantages and disadvantages

It is important to understand the main differences with steam cycles that make ORCs attractive, as well as the main drawbacks that can arise and that can be found in literature [5], [6], [25]

3.1.1) Advantages

- The main advantage, as previously introduced, is its low temperature heat recovery coming from using an organic compound as working fluid, as they have a lower boiling point than water. So, it makes possible to generate power from low heat source temperatures.
- Another important feature of organic fluids is that most of them have a positive or isentropic slope in the saturation vapor line on the T-s diagram (Figure 18). Consequently, they remain superheated at the end of the expansion so, contrary to steam cycles there is no need for superheating.

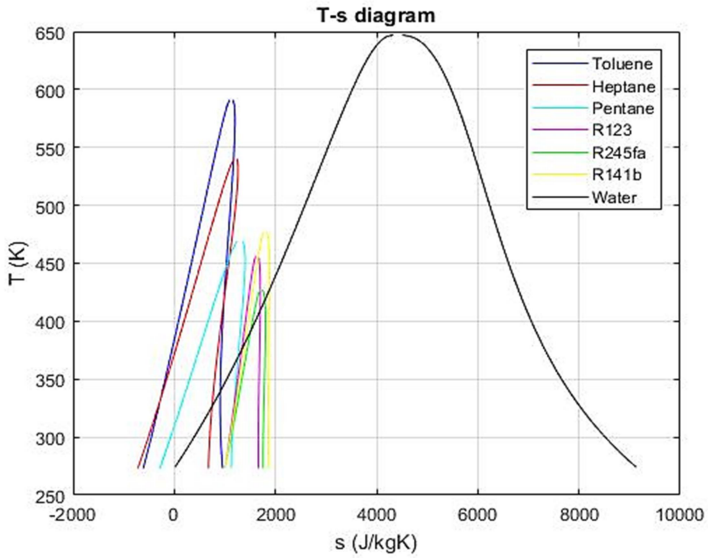


Figure 18: T-s diagram of water and some organic fluids from CoolProp Data Base in Matlab

- The turbine inlet temperature, which in steam Rankine Cycles is required to be higher than 450ºC due to the superheating constraint, will be lower, avoiding higher thermal stresses not only in turbine blades, but also in the boiler, thus reducing costs and increasing lifetime.
- With respect to the fluid density, in steam cycles vapor density is much lower, so for the ORC, less volume flow rate will be needed, leading to a reduction of the components size (pipes, heat exchangers, turbine…).
- In ORCs once-through boilers can be used, avoiding steam drum and/or recirculation. The reason for this difference with respect to steam cycles relies in the different heat transfer and pressure drop characteristics between water and steam provoked due to the low vapor density in the steam boiler, while density difference between vapor and liquid for organic fluids is relatively smaller.
- While in steam cycles pressures of 60-70 bar are reached, in organic ones, pressure does not exceed 30 bar so we find lower thermal stresses and then lower complexity and costs.
- As in the steam cycles pressure ratio, and then enthalpy drop in the turbine are very high, needing to perform the expansion through several stages while for ORCs, this enthalpy drop is much lower so it can be performed in a single or two stages which reduces costs. In addition, lower enthalpy drop means lower rotating speeds which may lead to the possibility of avoiding using a reduction gear in the electric generator.
- Low maintenance work required which leads to low personnel and O&M costs.

3.1.2) Disadvantages

- The main disadvantage of ORCs is its low thermal efficiency that does not exceed 24%, while conventional steam Rankine Cycles exhibit efficiencies higher than 30% although it must be considered that cycle design results more complex in terms of components number or size.
- Using an organic fluid instead of water means a disadvantage in some aspects as water results very convenient due its availability and low cost. In addition, water is a non-toxic, non-flammable, environmentally-friendly, chemically stable and low viscous fluid, positive characteristics that some organic fluids do not exhibit.
- Pump consumption, which is proportional to the liquid volume flow rate and pressure difference, will be higher for organic fluids.

3.2) ORC process description

As previously introduced, ORC process is going to be similar to conventional steam Rankine Cycle process in terms of layout and components. The organic fluid is heated in the evaporator generating vapor at high pressure after which it is expanded in the turbine that generates the mechanical energy converted to electrical by the generator. Then in the condenser heat is evacuated and vapor is converted to liquid phase that will then pass through the pump to increase its pressure before entering again the evaporator.

However, this layout is going to result simpler than for conventional plants, because as introduced in the previous part, just one turbine stage will be needed and there is no need for steam drum, while just one heat exchanger will perform the three evaporation steps: preheating, vaporization and superheating.

For the cycle architecture, in literature, authors coincide in stating that variations are constrained, for example reheating and turbine bleeding tend not to be suitable for ORCs [6] . A standard in ORCs is implementing a recuperative cycle, by adding a recuperator at the end of the expansion in order to take advantage of the remaining heat so that it preheats the fluid before entering in the evaporator as we can appreciate in Figure 19. In this way, less heat is needed to evaporate the fluid.

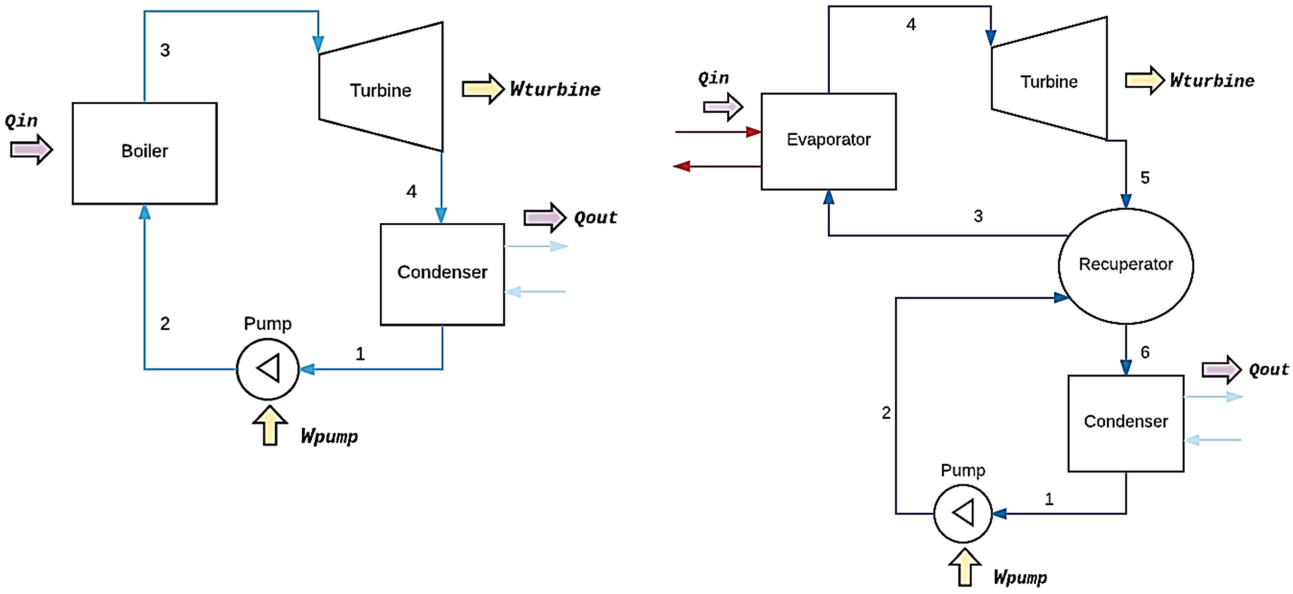


Figure 19: Simple Rankine (left) and Recuperative Rankine (right) Cycles

Depending on its application, these simple architectures represented in Figure 19 will be optimized and accommodated (main applications are briefly commented in section 3.3).

Heat transfer from the hot side (that in the project case will be the flue gases resulting from biomass combustion), can be performed in two different forms:

- Direct exchange of heat between the heat source medium and the organic medium.

- Through and intermediate thermal oil loop. This manner constitutes a standard in ORCs for biomass-fired plants. The purpose to integrate this intermediate loop is ensuring safety, avoiding risky contact between the heat source which is at very high temperatures and organic medium that could deteriorate if reached its maximum chemical stability temperature. In this way, it is easier to control and keep the system stable, as this loop softens variations of the heat source so smoother cycle operation is achieved.

3.3) ORCs for Biomass-fired plants

Although this project is focused on biomass power plants, ORCs have other important applications: geothermal energy, solar power plants and waste heat recovery in mechanical equipment and industrial processes or internal combustion engines. In addition, new innovative applications are appearing for example in solar pond power systems, solar systems for desalination with reverse osmosis or for cold production.

Processes described hereafter will be characteristic of biomass-fired plants which are the project scope. These kinds of plants have already been propitiously demonstrated and they can be found commercially available as it will be further demonstrated in section 3.5). This kind of plants range 0.4-2 MW electric according to literature [5], [6], [25],[26], power range in which using water as working fluid would not be cost effective. These plants constitute small units which are decentralized and whose electricity generation cost is generally not competitive. For this reason, combined heat and power is the trend in these plants as it can be found in literature because it ensures profitability of the investment due to higher conversion efficiencies. This is one of the reasons for the power limitation in these plants as heat cannot travel long distances due to losses so they tend to be limited to 6-10 MW thermal power, which corresponds to an upper limit of 1-2MW electric power as commented before.

As reference case for further optimization a simplified diagram of the system has been represented in Figure 20.

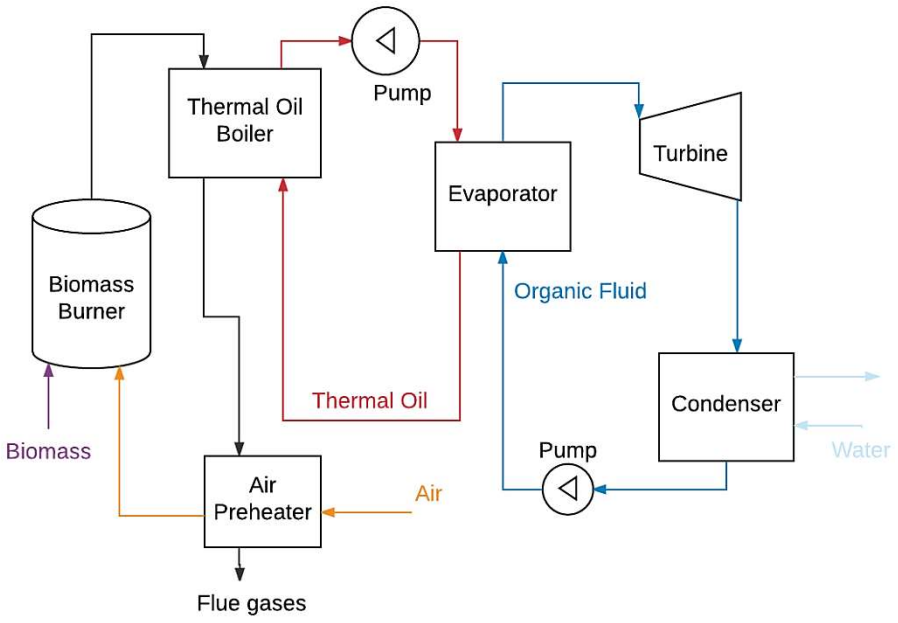


Figure 20: Simple reference Biomass-fired Power Plant based on ORC technology with intermediate thermal oil loop

The electrical efficiency is one of its main concerns, as it tends to range just between 6 and 18% as it can be found in literature. Although this is a limited value, the overall efficiency taking into account heat produced is used, would be around 88% [6]. To achieve this, heat losses through the flue gases must be reduced as much as possible by cooling them down, but taking into account that the acid dew point must not be reached. A schematic of the energy flow is presented in Figure 21, without taking into account system losses.

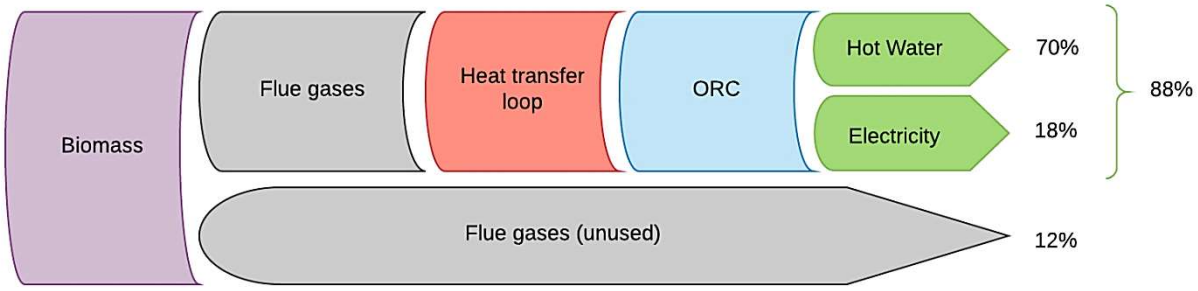


Figure 21: Energy flow in ORC systems for CHP

An air preheater has been included in the reference plant chart in Figure 20, in order to increase air temperature before biomass combustion takes place. The idea is to preheat the air in order to increase combustion efficiency by using residual heat unused in flue gases.

3.4) Working fluid selection

The selection of the appropriate working fluid is one of the key aspects of ORCs, as it will impact considerably on the cycle performance.

The main aspects to take into account when selecting the working fluid will be:

- Thermodynamic performance: efficiency and power output must be as high as possible. They depend on fluid thermodynamic properties such as critical point and density among others.
- Saturation vapor curve should be positive or isentropic to ensure dryness at the end of the expansion to avoid turbine damage.
- High vapor density, as it means lower volume flow rate needed and then lower components size, reducing considerably costs.
- Low viscosity in both phases to reduce friction losses and increase heat transfer coefficient in heat exchangers.

- Evaporating pressure should be as low as possible to reduce complexity and costs.
- Condensing pressure should be higher than atmospheric to avoid air infiltration into the cycle enhanced by this difference in pressures.
- It is needed to be careful with the maximum temperature that the fluid reaches to avoid chemical deterioration and with the melting point, that should be lower than minimum ambient temperature in the selected location to avoid it to freeze during shutdowns, thus ensuring the system stability.
- Toxic and flammable fluids must be avoided.
- Fluids with good availability and price are preferred.
- Environmentally friendly fluids are preferred, so that they do not contribute to global warming.

In this project, different fluids are going to be analyzed and the most appropriate one will be selected according to the above conditions.

3.5) Market evolution and manufacturers

First ORC manufacturers appeared in 80s [6] and they have suffered an important evolution until today. The distribution of the actual installed capacity of ORCs in the world per application is the shown in Figure 22.

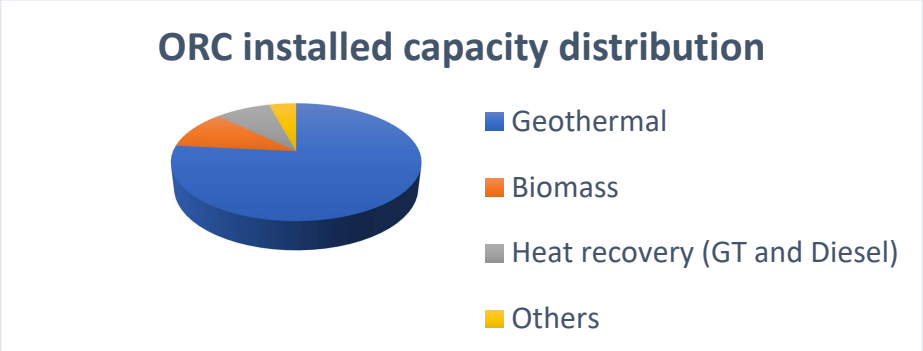


Figure 22: Distribution of the installed capacity of technologies using ORC

Most of it belongs to geothermal power plants, around 76.5%, followed by biomass that accounts for 10.7%. Heat recovery from gas turbines and stationary Diesel power plants means an 8.5% and the remaining technologies account for 4.2%. As it can be appreciated contribution from solar power plants to the installed capacity of plants using ORC is still inconsequential.

Currently it is estimated there exists a total installed capacity of 2749.1 MW electric in 563 power plants, taking into account that cases with less than 50kW electric of installed capacity have been neglected.

The evolution to reach the actual situation is illustrated in Figure 23, where it can be appreciated that ORCs have been linked from its beginning to geothermal applications until the end of the 90s when new projects regarding biomass and heat recovery applications started to be developed.

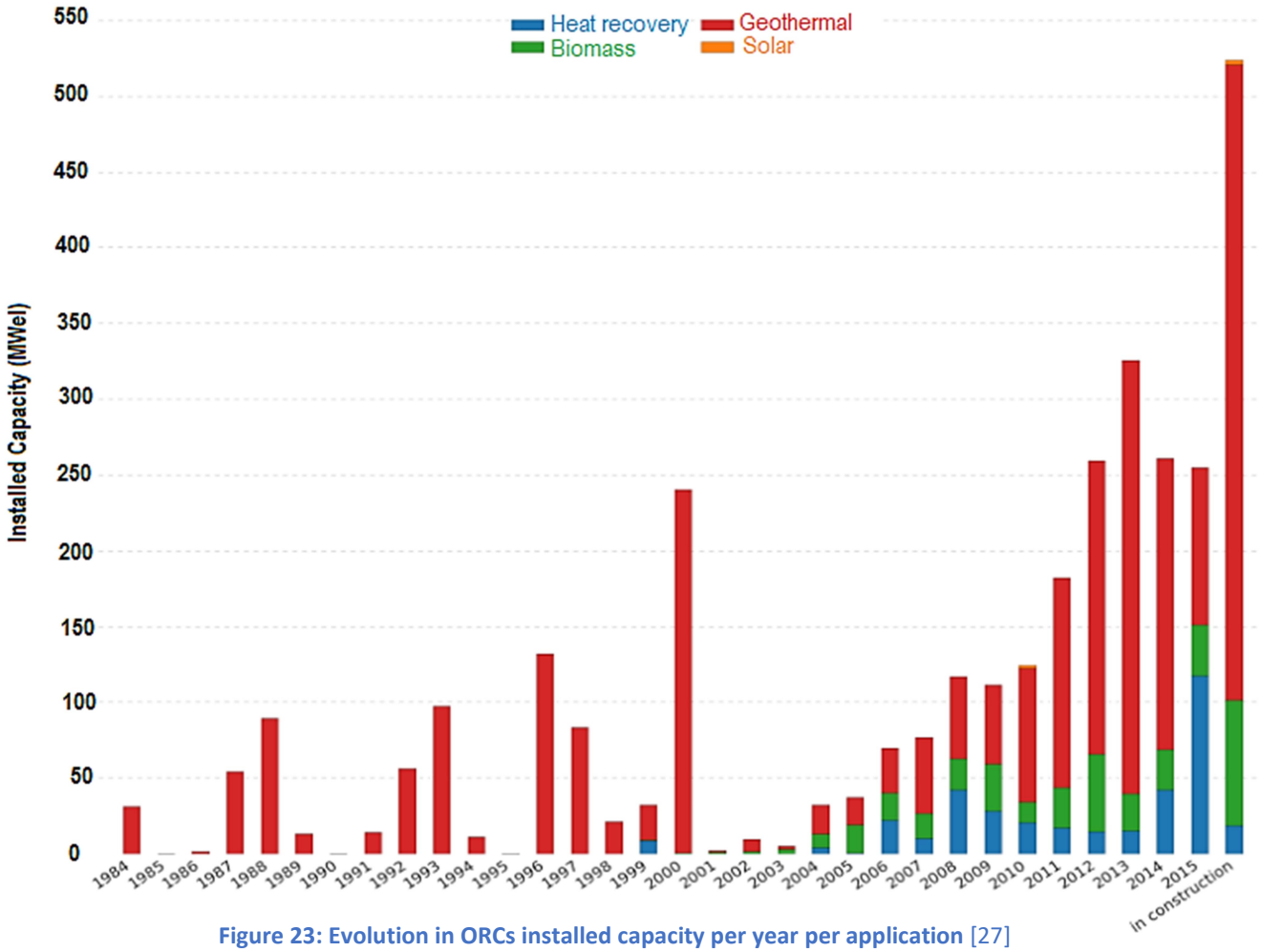


Figure 23: Evolution in ORCs installed capacity per year per application [27]

Although this technology started to be developed many years ago, it has started to become popular in recent years, and this is due to the growing interest in decentralization of power plants and the recovery of medium and low-grade energy.

The market peak corresponds to 2013, and the decline from them might be caused by the decrease in natural gas prices, which increased the share of fossil fuels in the energy mix, and caused the reduction of geothermal applications, although biomass has remained more or less constant.

It is important to notice that although installed capacity for geothermal applications continues being the trend, if we look at the number of installations in Figure 24 it changes.

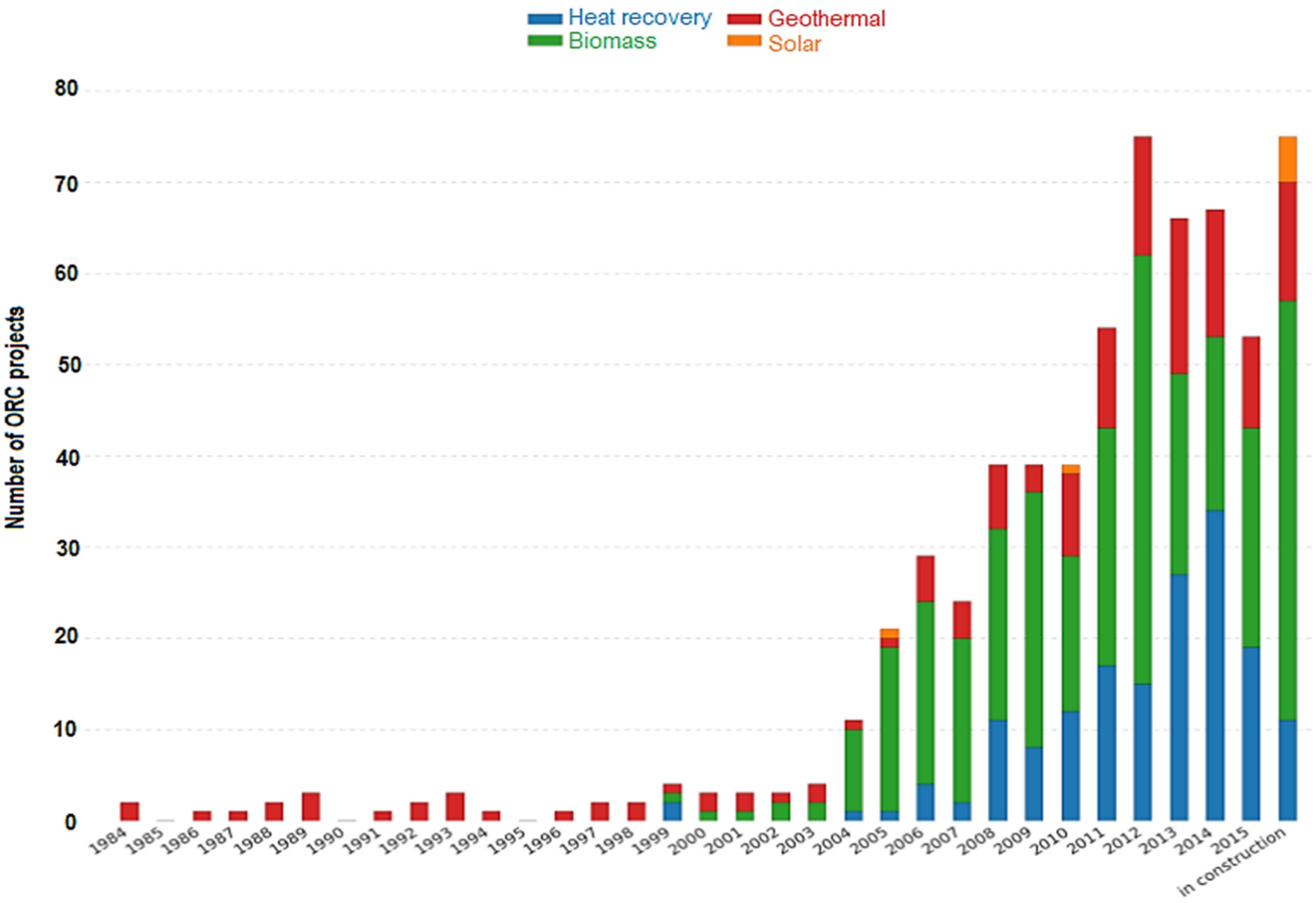


Figure 24: Evolution in number of ORC projects per year per application [27]

From 2004 on, in most of the years the dominant application in terms of number of projects commissioned is biomass, having an important increase over the years and with high expectations for the future, as it was the leader in projects under construction in year 2016. This difference with previous graph is explained by the range of installed capacity that for biomass power plants is much lower while geothermal constitutes the application with larger capacities.

From this graph, it can also be concluded that solar applications are expected to increase its presence in this market.

The main manufacturers of ORC are shown in Figure 25, from which it is concluded that ORMAT is the leader manufacturer with a share of 65.7%, followed by Turboden and Exergy. ORMAT leadership is due to its focus on low temperature large-scale

geothermal binary plants, that as we know from previous graphs is the predominant application.

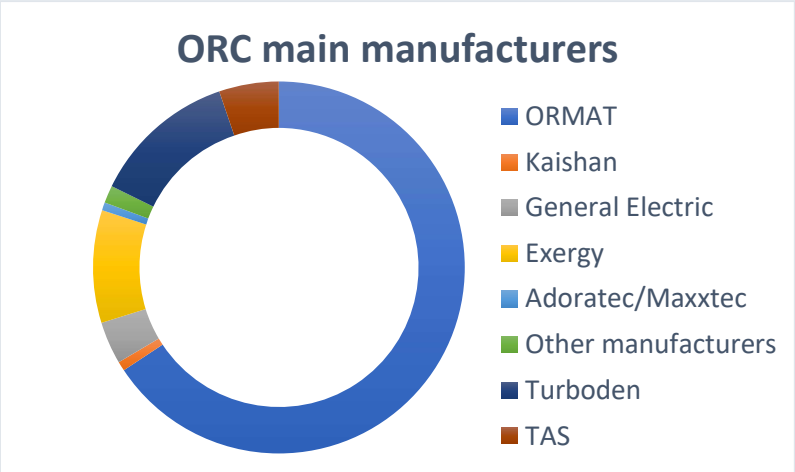


Figure 25: ORC main manufacturers

We must take into account that there are many other small manufacturers, not included in the survey from which data have been obtained [27]. This work is not exhaustive but as most of the existing ORC plants have been considered it provides a general idea of the current situation, updated up to 2016.

USA appears in the survey as the country with largest installed capacity, doubling the capacity of the next one following him which is Turkey. Both countries interest has been focused on geothermal applications.

But regarding the future Italy appears as the country which is intended to develop more number of projects, most of them focused on biomass applications and with an important presence of solar and waste applications. In some other countries expecting an important number of new projects with ORCs (United Kingdom, Russia, Canada, Switzerland…) the trend is the same, higher presence of biomass applications followed by waste heat recovery. So according to this a decline in geothermal applications is foreseen, although currently it is still by far the main application using this technology in terms of power output.

4. ORC PROCESS DESIGN

In this section, ORC operation is simulated in MATLAB, using CoolProp Database to develop the thermodynamic model. Starting from the simple configuration, this model will make possible to implement potential improvements whose objective will be focused on the enhancement of electrical efficiency and net power output. To optimize the model several fluids are going to be tested under the same conditions to select the most suitable, testing also the different cycle architectures to identify also the most appropriate one.

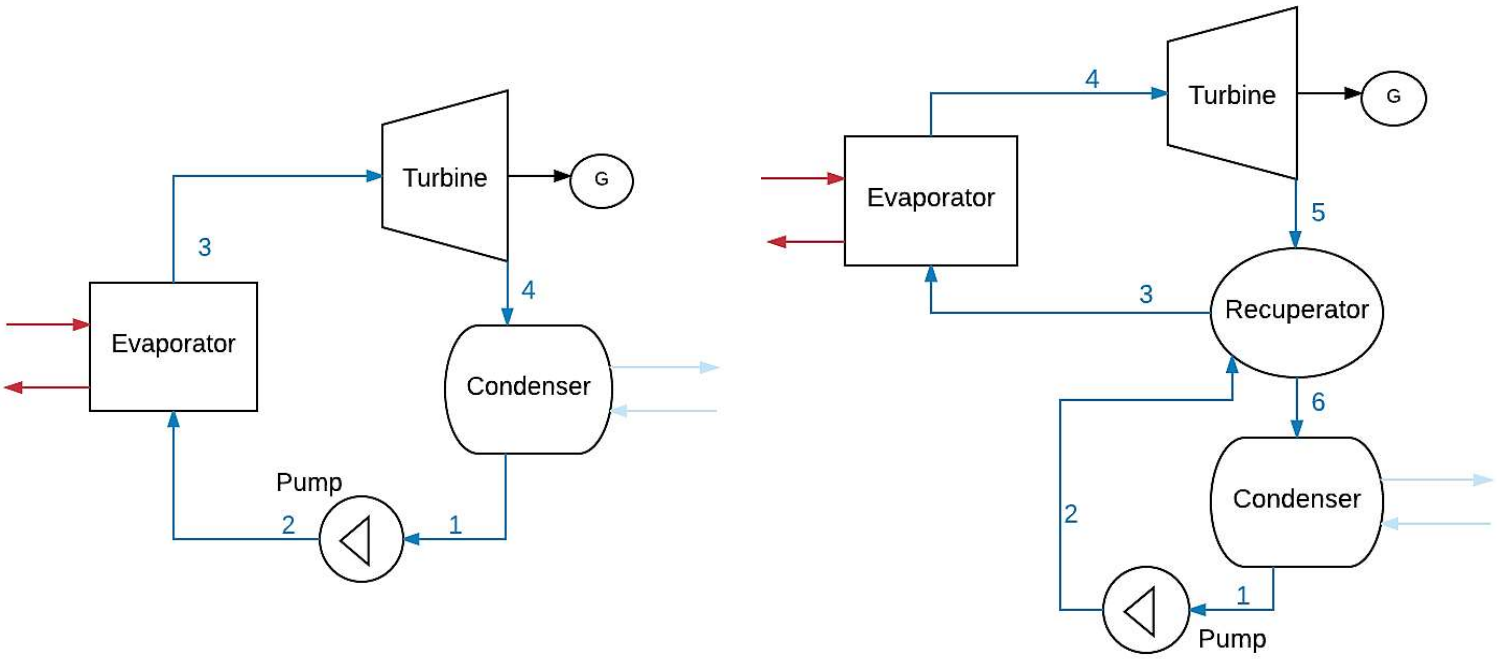
According to working fluid guidance developed in 3.4), the selection criteria that this project follows will start by selecting common fluids used for this kind of applications based on literature. From the initial number of fluids some of them will be removed due to unsuitability for working temperatures range or unacceptable environmental impact, which means they are phased out because of being too climate-harmfully. After this initial reduction in the fluids to test, simple configuration will be simulated in order to analyze thermodynamic performance in terms of efficiency and net power output. At this point the most thermodynamically unqualified fluids will be dismissed to finally study the behavior of a reduced number of fluids of interest. This reduced number of fluids will be tested for the different additional configurations that are proposed in the next section, 4.1), examining physical properties of interest according to working fluid selection criteria, so that finally the most suitable organic fluid for our case study plant could be selected.

4.1) Cycle configurations case studies

Three ORC schemes will be analyzed in order to get to know the optimal layouts of the system. These schemes are a simple, recuperated and reheated cycle which configurations are illustrated in Figure 26.

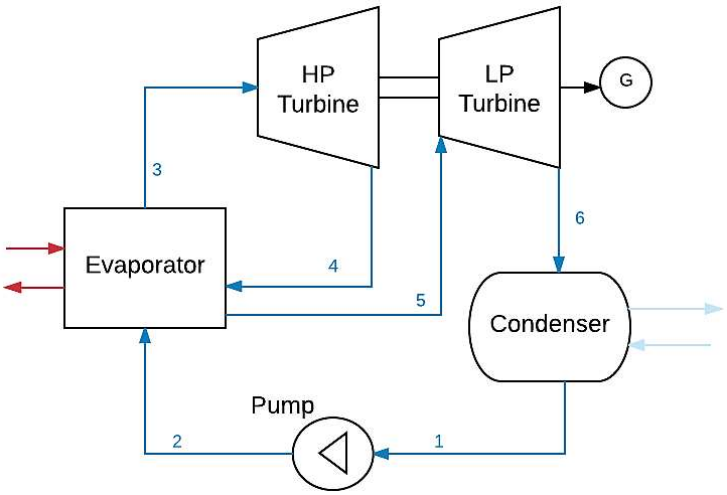
Simple configuration includes the evaporator, turbine, condenser and pump that are specific of a conventional Rankine Cycle. The recuperated cycle, Figure 26b), additionally includes a heat exchanger at turbine outlet in order to transfer heat from high temperature working fluid at turbine outlet to low temperature working fluid at pump outlet before entering the evaporator so that the efficiency increases. In the reheated cycle we can also improve the cycle performance by expanding the fluid in two stages with a reheating process in between as it can be appreciated in Figure 26 c). It is performed by isentropically expanding the working fluid in vapor phase to an intermediate pressure, then passing it again through the boiler to reheat it at a

constant pressure and finally performing the second isentropic expansion to the condenser pressure.



a) Simple Configuration

b) Recuperated Configuration



c) Reheated Configuration

Figure 26: Plant layouts to be analyzed

4.2) Specifications in terms of cycle parameters

To calculate thermal efficiencies and net power outputs and to identify the most adequate fluid, we must consider some design parameters for the cycle.

Main parameters to take into consideration are maximum and minimum process temperature. Maximum temperature is limited by the fluid stability so that it must be lower than the temperature at which the working fluid starts to deteriorate and decompose chemically. In literature, maximum temperature habitual for already existing biomass ORC units is said to be 573K [28]. Aware that this temperature strongly impacts the results obtained, it will be analyzed varying it in a range between 523K and 623K. We must take into account that some fluids might not result appropriate for this range as their maximum stability temperature could be lower, if this is the case, maximum temperature reached by that particular fluid will be set as its maximum stability temperature.

For the minimum temperature of the cycle, if we appeal to literature, it can be found that in order to operate as a CHP plant, the condensing pressure needs to be at least 363K while for operating just to produce electricity it should be lower, around 313K, as the lower the condensing temperature, the higher power it is produced. As it will be simulated so that it can work as a CHP plant, condensing temperature will be 363K.

Maximum pressure has been set to 1MPa. The higher maximum pressure, higher power it is produced. The reason for this limitation has been an overview of already existing ORC modules that tend to establish this limit to cut down safety measures and material costs [29].

Organic fluid mass flow rate has been approximately estimated according to similar existing power plants and projects with similar design conditions in literature that take into account other parameters specially related to feasibility. The higher the mass flow rate, higher net power output obtained, but also it will be needed greater components that could increase too much plant costs. Value set for mass flow rate has been 10 kg/s.

A summary of the main input parameters is provided in Table 3 and other necessary assumptions have been listed in Table 4.

Parameter	Value
Maximum Temperature (K)	523 - 623
Minimum temperature (K)	363
Maximum Pressure (MPa)	1
Mass flow rate (kg/s)	10
Turbine isentropic efficiency (%)	85
Pump isentropic efficiency (%)	80

Table 3: Main ORC Parameters Setting

Assumptions
No pressure drops in heat exchangers
Kinetic and potential energy effects are negligible
Pressure and heat losses in pipelines are negligible
Saturated liquid at pump inlet
Atmospheric Pressure: 0.974 bar (selected according plant location)

Table 4: Cycle assumptions

Some constraints need to be considered when selecting an appropriate fluid. Maximum and minimum process temperature as well as maximum process pressure has already been set as inputs considering application and stability of the fluid and materials. Some other constraints need to be checked when simulating the thermodynamic cycle. As explained in section 3.4, melting temperature should be higher than the minimum ambient temperature to avoid freezing, evaporating pressure should be lower than critical to avoid supercritical region and turbine outlet dryness needs to be higher than 90% in order to avoid turbine blades to damage. It will be also taken into account that lower condensing pressures mean increased plant costs and complexity so too low pressures should be avoided. A summary of these constraints is provided in Table 5.

	Constraints	
Evaporation P	<Critical Pressure	Depends on fluid (Table 5)
Maximum Process T	<Maximum fluid temperature	Depends on fluid (Table 5)
Melting T	<Minimum ambient temperature	<273K
Turbine outlet dryness		>0.90

Table 5: Main ORC Constraints

Fifteen fluids have been selected for the optimization, based on other studies in literature, that suggest them as the most suitable for this kind of applications [30], [28], [5], [6]. These fluids are presented in Table 6, as well as some important thermodynamic and environmental properties such as critical temperature and pressure, maximum temperature, evaporating temperature, environmental danger in terms of ODP and GWP, and NFPA 704M label in order to provide a reference to compare toxicity, flammability and fluid stability (further explanation below). These properties, except from the NFPA 704M label classification, have been obtained from CoolProp Data Base.

Working Fluid	Critical Temperature (K)	Critical Pressure (MPa)	Maximum Temperature Limit (K)	Evaporating Temperature (K)	ODP [a]	GWP [b] (100yr)	NFPA 704M Label [c]
1- Toluene	591.7500	4.1260	700	489.9456	0	3.3	
2- Heptane	540.1300	2.7360	600	474.3042	0	0	
3- Pentane	469.7000	3.3700	600	398.0725	0	0	
4- R123	456.8310	3.6720	600	384.3020	0.02	77	
5- R245fa	427.0100	3.6510	440	362.8991	0	1030	
6- R134a	374.2100	4.0593	455	312.5376	0	1430	
7- Ethylbenzene	617.1200	3.6224	700	521.6636	0	0	
8- R365mfc	460.0000	3.2662	500	396.7417	0	794	
9- R12	385.1200	4.1361	525	314.8703	1	10900	
10- R141b	477.5000	4.2120	500	391.5285	0.12	725	
11- Ethanol	514.7100	6.2680	650	423.8447	0	0	
12- m-Xylene	616.8900	3.5346	700	524.0321	≈ 0	0	
13- p-Xylene	616.1680	3.5315	700	523.8206	≈ 0	0	
14- o-Xylene	630.2590	3.7375	700	531.1081	≈ 0	0	
15- MDM	564.0900	1.4100	575	541.4678	0	0	

Table 6: Working fluids characteristics

[a] ODP: Ozone Depletion Potential. It is the level of degradation a chemical compound can produce to the ozone layer relative to R11, being fixed at an ODP of 1.0. It is the ratio of global loss of ozone of a determined substance to the one due to R11 with the same mass.

[b] GWP: Global Warming Potential. As its name suggests it shows the potential a substance has to contribute to global warming. It measures the amount of heat a gas can trap in the atmosphere compared to the one of a similar mass of CO_2, which is commonly used as the reference gas. It is calculated in a determined time period, usually 20, 50 or 100 years. In this case time interval selected has been 100 years.
Data for ODP and GWP has been obtained from CoolProp Database. These two measures together are commonly used to provide a measure of how environmentally adverse a substance can result.
[c] NFPA 704M label: Standard System for the Identification of the Hazards of Materials for Emergency Response. More information provided on Appendix 8.3.

As previously commented not all fluids will result suitable for the temperature range that will be tested for maximum process temperature, therefore before optimizing it for each fluid, some fluids which maximum temperature is below 523K can be dismissed. As it can be seen more clearly in Figure 27, fluids that result non-viable in this aspect are R245fa, R134a, R365mfc and R141b.

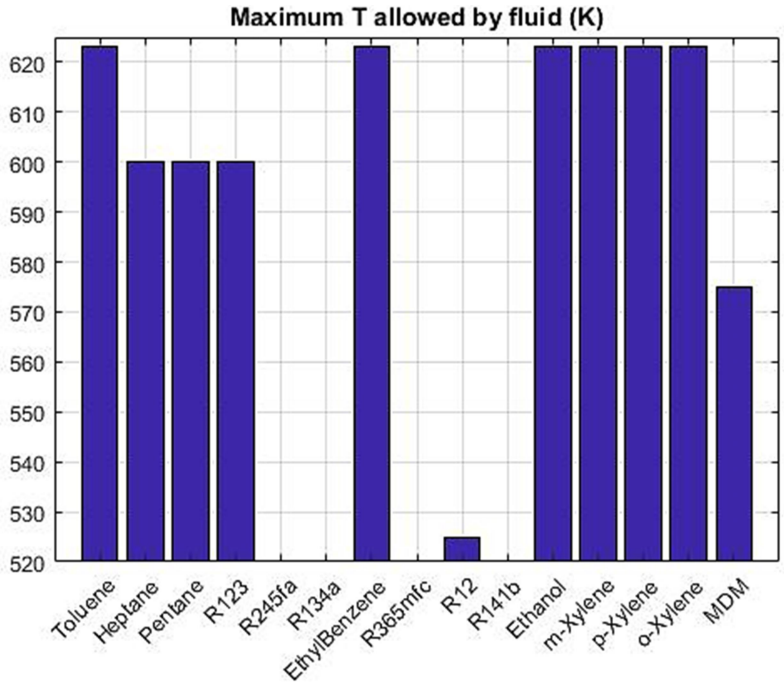


Figure 27: Working temperature range allowed by fluid

It will also be removed from the study those fluids which are phased out due its high environmental impact that they have high ODP or GWP. Then from the remaining 11 fluids R12 is going to be removed for this reason, because as it can be checked in Table 6 it exhibits an extremely high GWP.

Now the remaining 10 fluids are going to be tested for the three simple scheme calculating their corresponding efficiencies and power output according to equations in Table 7 in order to evaluate the thermodynamic performance of the ORC system.

Table 7 has already included equations needed to calculate net power output and efficiency that we will use further on.

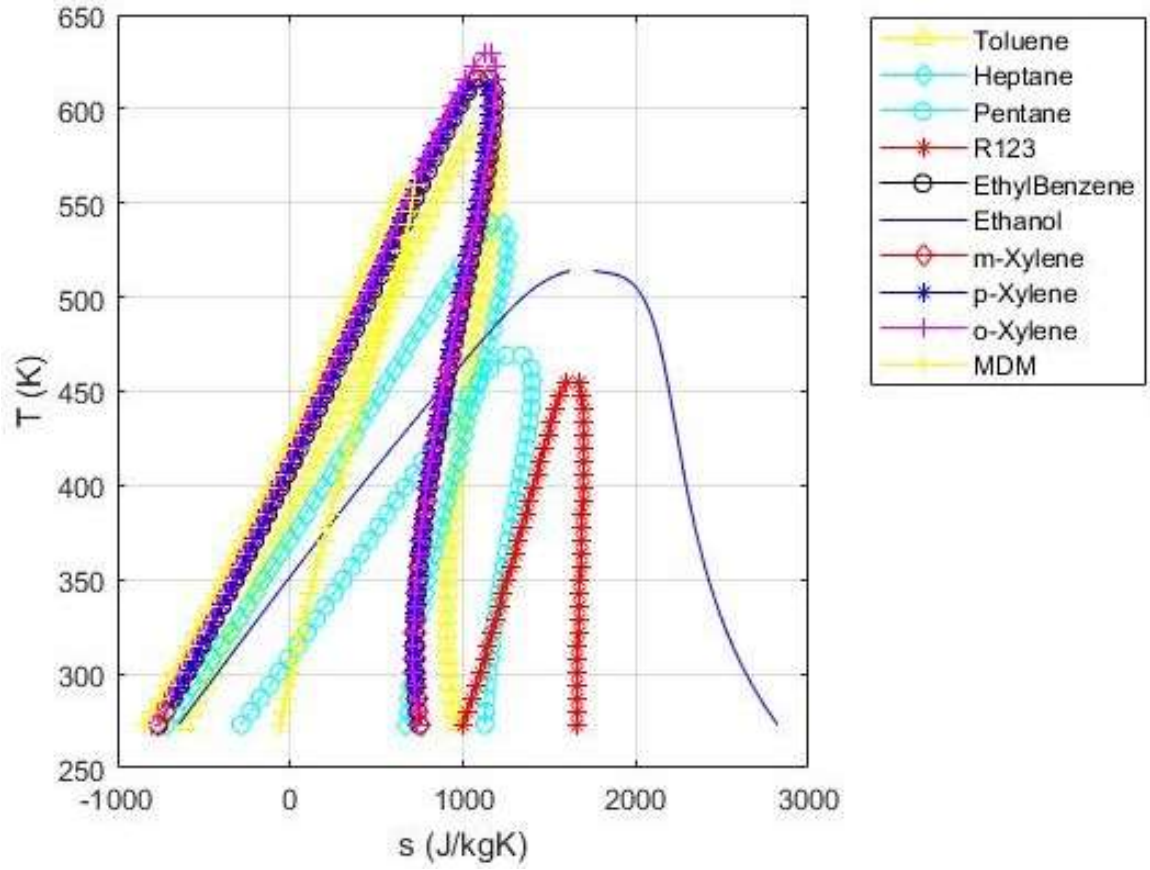


Figure 28: T-s chart comparison of the case study fluids (from CoolProp Properties)

Figure 28 shows the entropy-temperature diagrams for the fluids being analyzed. As we can check on it, the only "wet" fluid would be the Ethanol, as it has a negative saturated vapor curve slope. R123 is an isentropic fluid and the rest of them belong to "dry" fluids. As commented in 3.4), fluids preferred are isentropic or dry ones, in order to avoid superheating, and the added costs and complexity that it implies. In spite of this fact, ethanol is not going to be dismissed until its thermodynamic performance is analyzed.

Furthermore, it can be appreciated very similar curves for Ethylbenzene, m-Xylene, p-Xylene and o-Xylene, so a similar behavior is expected for these four.

MAIN ORC EQUATIONS			
Parameter		**Equation**	**Configuration**
Net power output	$Wnet$	$Wnet = Wturbine - Wpump$	All configurations
Thermal efficiency	ηth	$\eta th = \frac{Wnet}{Qin}$	All configurations
Power generated by the turbine	$Wturbine$	$Wturbine = \dot{m} \cdot (h_3 - h_4)$	Simple
		$Wturbine = \dot{m} \cdot (h_4 - h_5)$	Recuperated
		$Wturbine = \dot{m} \cdot ((h_3 - h_4) + (h_5 - h_6))$	Reheated
Power consumed by the pump	$Wpump$	$Wpump = \dot{m} \cdot (h_2 - h_1)$	All Configurations
Input thermal power	Qin	$Qin = \dot{m} \cdot (h_3 - h_2)$	Simple
		$Qin = \dot{m} \cdot (h_4 - h_3)$	Recuperated
		$Qin = \dot{m} \cdot ((h_3 - h_2) + (h_5 - h_4))$	Reheated

Table 7: Main ORC equations depending on the configuration

4.3) Results and Discussion

Before comparing the results obtained for the different configurations and the improvements they bring, simple configuration will be analyzed, as similar behavior of the fluids is expected for the three of them.

Figure 29 shows the efficiency obtained when simulating the simple configuration for the remaining 10 fluids under study, depending on the maximum process temperature varying it as previously stated from 523 to 623K. The results obtained show that there are five fluids we can dismish due to the poor efficiency obtained at any of the temperatures from the range analyzed. The most obvious ones are R123 and pentane. By looking at Figure 29, it can be appreciated that R123 and pentane exhibit the lowest critical temperatures. Critical temperature strongly impacts thermodynamic performance and there are many studies recommending choosing the fluids with highest critical temperature, although this also means lower vapor density, and then increased system costs. Increased critical temperature means increased evaporating temperature [31], as it can be checked, these two fluids also exhibit the lowest

evaporating temperatures. Many studies have set evaporating temperature as one of the main features impacting thermal efficiency [28], [30], [32].

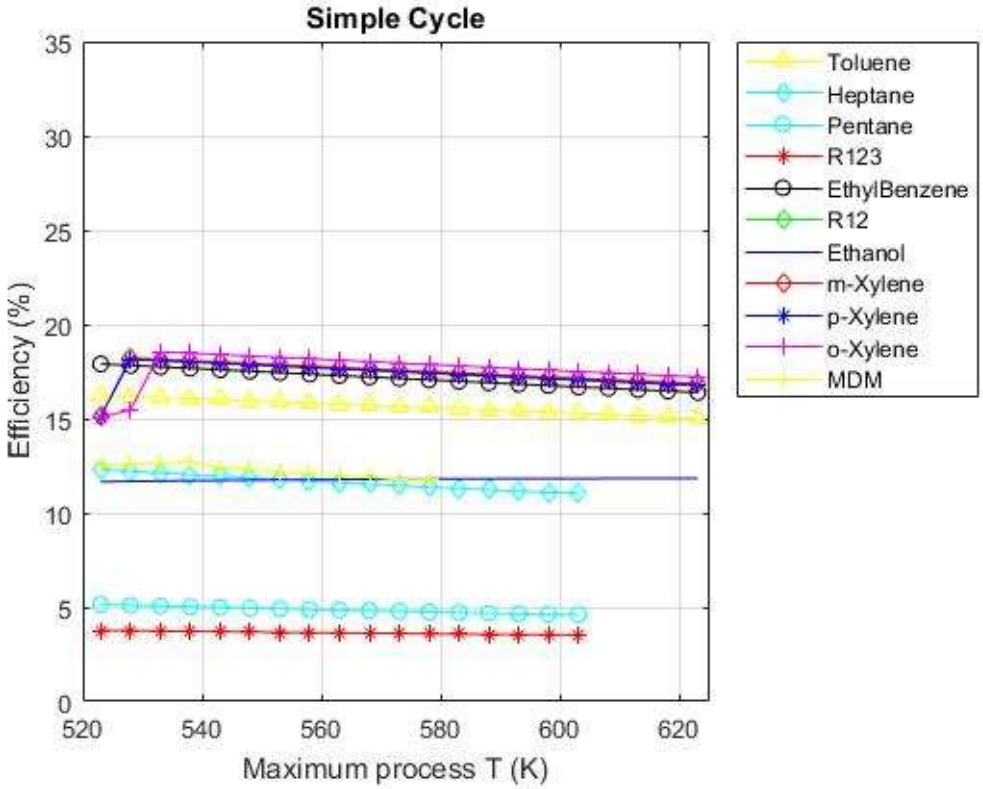


Figure 29: Efficiency depending on maximum temperature for the selected fluids

In Figure 29 it can be appreciated that there are two fluids that can also be removed from the selection study because of its low efficiency: MDM and heptane. They exhibit higher critical temperatures than pentane and R123, but still not enough to compete with the remaining ones. Although ethanol has considerably lower critical and evaporating temperature than MDM and heptane it gets similar efficiencies. The reason may lay in the vaporization enthalpy, the latent heat, which also impacts efficiency and which is quite higher for ethanol than for MDM and pentane. Although ethanol efficiency is considered very low compared to other fluids present in the study and as it can be appreciated in Figure 29, it will still not be removed from the study due to its interesting results in terms of net power output as it can be checked in next figure.

Basically at this point there are five fluids that result competitive in terms of efficiency: toluene, ethylbenzene, m-xylene, p-xylene and o-xylene although we will keep analyzing ethanol due to its considerably higher net power output, hence these six fluids will remain being taken into account as possible options for the biomass power

plant operation. As commented previously, fluids with similar shape show similar results, so toluene and ethanol, which differ from the rest of them, present a more different behavior. Figure 30 represents the net electrical power produced by these six fluids, again for the different maximum temperatures.

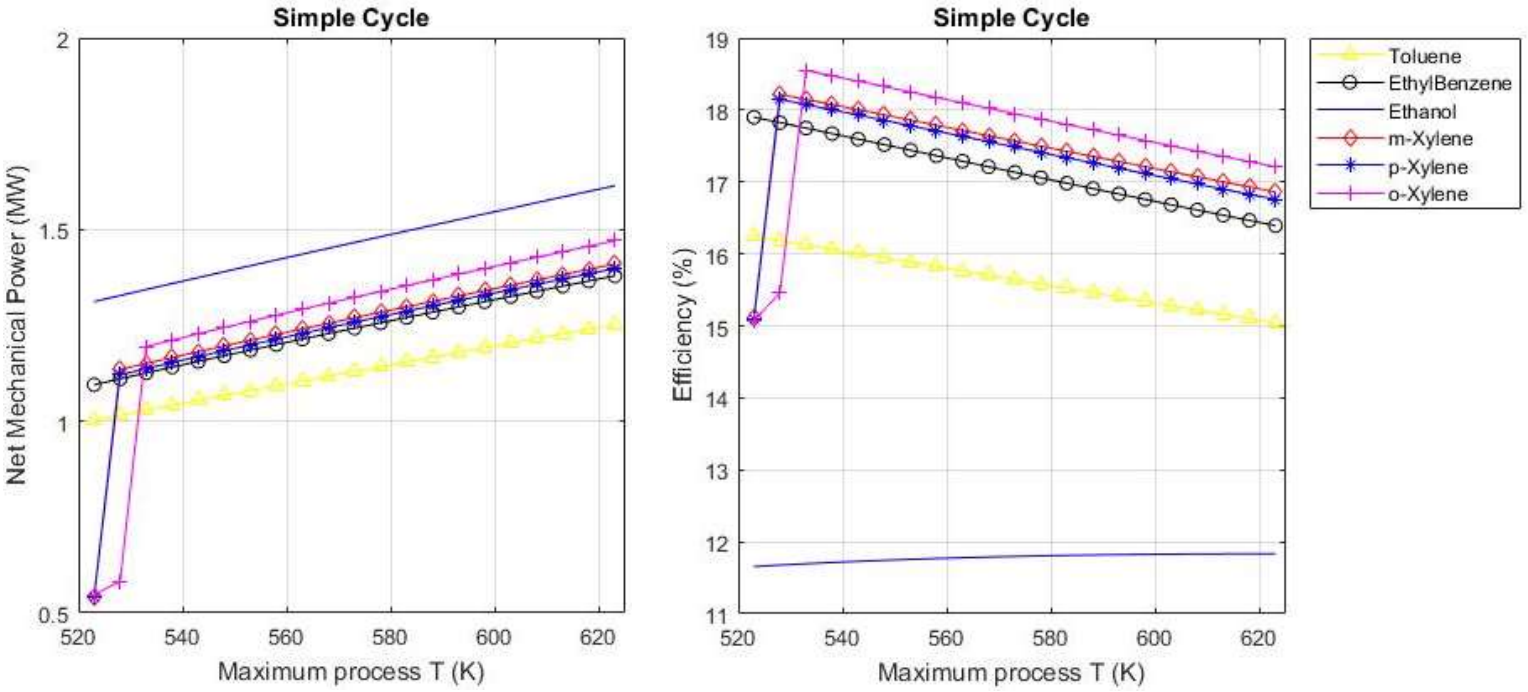


Figure 30: Net power output and efficiency depending on maximum temperature for the selected fluids

From 532K on, the fluid presenting highest net power output has been ethanol. Ethanol has achieved around 146kW more than o-xylene while o-xylene is exhibiting less than 100kW more net mechanical power than ethylbenzene (72kW lower), p-xylene (60kW lower) and m-xylene (47kW lower) respectively, while the difference with Toluene is a little higher, around 174kW.

In terms of efficiency, o-xylene presents the highest efficiencies for maximum temperatures higher than 532K, but this difference is quite low as it only overcomes toluene, ethylbenzene, m-xylene and p-xylene in around 2.3%, 0.8%, 0.4% and 0.5% respectively. Ethanol has the lowest thermal efficiency and its behavior is different to the other ones as it increases with temperature while from 532K on, the efficiencies of all the others decrease with it. The reason might relay in the difference in the t-s

shape, as ethanol is a wet fluid. Its efficiency is around 6.5% lower than o-xylene varying depending on maximum working temperature.

For temperatures lower than 532K, o-xylene, m-xylene and p-xylene exhibit very poor net power output, and also efficiency results considerably lower. Reason may be explained in Figure 31, were it can be appreciated that for the lowest temperatures, dryness at turbine outlet is below 100% so impact of dryness at turbine outlet can be appreciated, not only it will damage turbine blades, but also it will be reflected in thermodynamic performance.

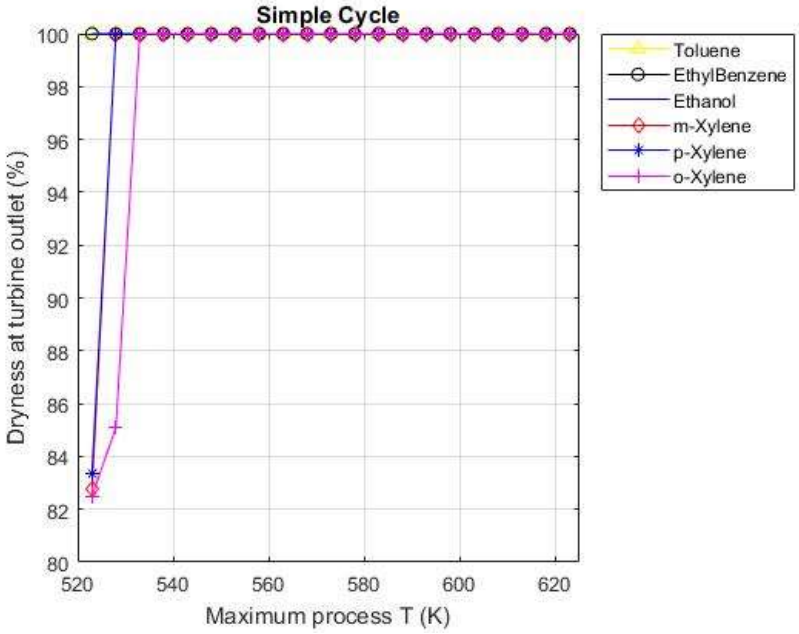


Figure 31: Dryness at turbine outlet depending on maximum temperature for the selected fluids

Resorting to NFPA 704M label to compare toxicity, flammability and reactivity it can be found out that the six of them are really similar in these terms. All of them are stable fluids in terms of reactivity, but they are considered easily flammable fluids. With respect to health hazard, all of them could represent a health hazard under continued and intense exposure, causing temporal incapacitation or residual injurie, except from m-xylene which exposure could only cause irritation with minor residual injury [33]. As they are really similar in this aspect, any of them can be dismissed due to security reasons. With respect to environmental friendliness, if we appeal to Table 6, it can be found that any of them represents a harmful regarding ODP and GWP.

Previously, it was commented that maximum temperature achieved in already existing plants of this type was 573K. Maximum temperature for the remaining fluids under study, presented in Table 6, is 700K for all of them, except from ethanol, which is 650K.

In order to be conservative and avoid risky operation due to temperature fluctuations and aware that the higher maximum temperature, higher costs will be faced; the maximum process temperature is going to be set to 543K. For this temperature, Table 8 shows the main results obtained for this simple configuration at the maximum process temperature selected.

Fluid	ηth (%)	Wnet (MW)	Condensing Pressure (bar)	h_{vap} (kJ/kg)	h_{drop} (kJ/kg)
Toluene	16.007	1.0545	0.540	273.707	106.9286
Ethylbenzene	17.595	1.1562	0.241	248.900	117.1319
Ethanol	11.728	1.3748	1.56	686.618	138.9323
m-Xylene	18.003	1.1814	0.218	252.812	119.6648
p-Xylene	17.929	1.1687	0.225	248.281	118.3940
o-Xylene	18.400	1.2282	0.184	254.496	124.3167

Table 8: Thermodynamic properties for maximum process temperature of 543K and simple configuration

Table 8 also brings information about the condensing pressure, where it can be seen that o-xylene exhibits the lowest, and it should be considered that this means higher cost of condenser purchase and also increased plant complexity. Ethanol presents the highest condensing pressure, and as it is higher than atmospheric, its use would simplify considerably the operation of the plant and would reduce condenser cost, as air infiltration is enhanced for condensing pressures lower than atmospheric, as previously explained.

As o-xylene, p-xylene and m-xylene results are really similar in terms of composition and then performance, from now on we will take o-xylene for the analysis instead of the three of them, and it will be compared to ethanol and toluene. The reason to choose o-xylene among these three similar fluids has been the obtainment of highest efficiency and net power output.

In Figure 32, T-s diagrams for o-xylene ethanol and toluene are represented. In this picture the influence of evaporating temperature can be appreciated. The higher efficiencies are obtained when superheating is avoided or reduced expanding it in or

closer to the saturated vapor line. This is one of the main reasons why o-xylene exhibits more efficiency than toluene.

Vaporization enthalpy is remarkably higher for ethanol as it is shown in Table 8, but as its evaporating temperature (Table 6) is quite lower, this makes the efficiency to be quite poor. Net power output on the contrary, is remarkably higher than for the rest of them, and the reason, as if it is appealed to Table 8 is the higher enthalpy drop.

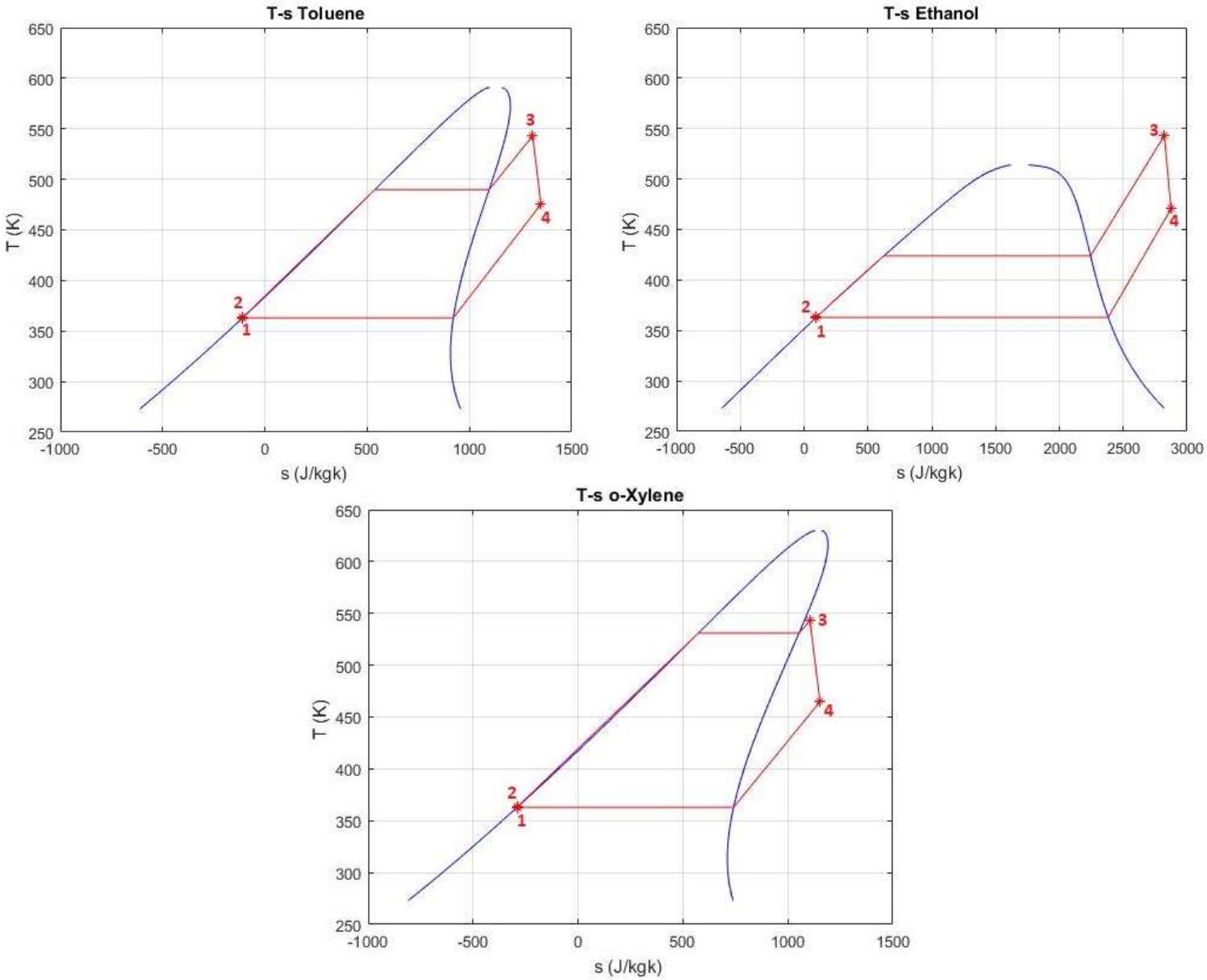


Figure 32: T-s diagram comparison between o-Xylene, toluene and ethanol at 543K maximum process temperature for simple configuration

Now the operation of these three fluids is going to be simulated for the improved configurations: reheated and recuperated, as the other fluids can be also dismissed because of the same reasons than for the simple one. The other three have been dismissed due to their similar behavior with o-xylene, and as this one has better thermodynamic properties, although slightly, it is the one selected to compare with toluene.

First, the reheated configuration, which has been previously described, has been simulated in Matlab, using again CoolProp Database. In order to simulate it, some more input parameters additional to the simple configuration ones need to be defined. The parameters defined have been the temperature reached after reheating vapor in the boiler, which is temperature at point 5 in Figure 29 c), and the pressure at which this extraction is performed. Reheating temperatures are really close or same as turbine inlet temperature, while optimum reheating pressure is close to a quarter of maximum cycle pressure [34]. So the values selected have been set, according to this at values showed in Table 9.

Additional input parameters for reheating case

Parameter	**Value**
Reheating temperature (K)	520
Reheating pressure (MPa)	0.25

Table 9: Additional input parameters for reheated configuration

The simulation has given the results presented in Table 10.

Fluid	ηth (%)	Wnet (MW)	Condensing Pressure (bar)	h_{vap} (kJ/kg)	h_{drop} (kJ/kg)
Toluene	15.773	1.075	0.540	273.707	108.976
Ethanol	11.328	1.405	1.564	686.608	142.013
o-Xylene	18.242	1.252	0.184	254.496	126.698

Table 10: Thermodynamic properties for maximum process temperature of 543K and reheated configuration

It can be checked that efficiency has decreased for the three of them contrary to the expectations. Efficiency has decreased a very small quantity, around 0.2% while from literature [34] it is known that efficiency is expected to increase around 5% for steam cycles applying this improvement therefore it does not apply for ORCs. The reason is that reheating not always increases thermal efficiency, although the enthalpy drop has increased a little as we can check in the table below, in order to increase efficiency mean temperature of heat addition in the boiler has to be higher than in the reheat

process, and this is not the case as mean temperature of heat addition in the boiler is 453.2K while in reheating process it is 514K.

With respect to net power output it has increased for the three of them as we have increased enthalpy drop, the increase has been of 21kW in the case of toluene, 31kW in the case of ethanol and 24kW in the case of o-xylene. As expected, the condensing pressure and vaporization enthalpy remain the same. Dryness at turbine outlet has been checked and it is 100% for the three of them at both turbine stages outlet.

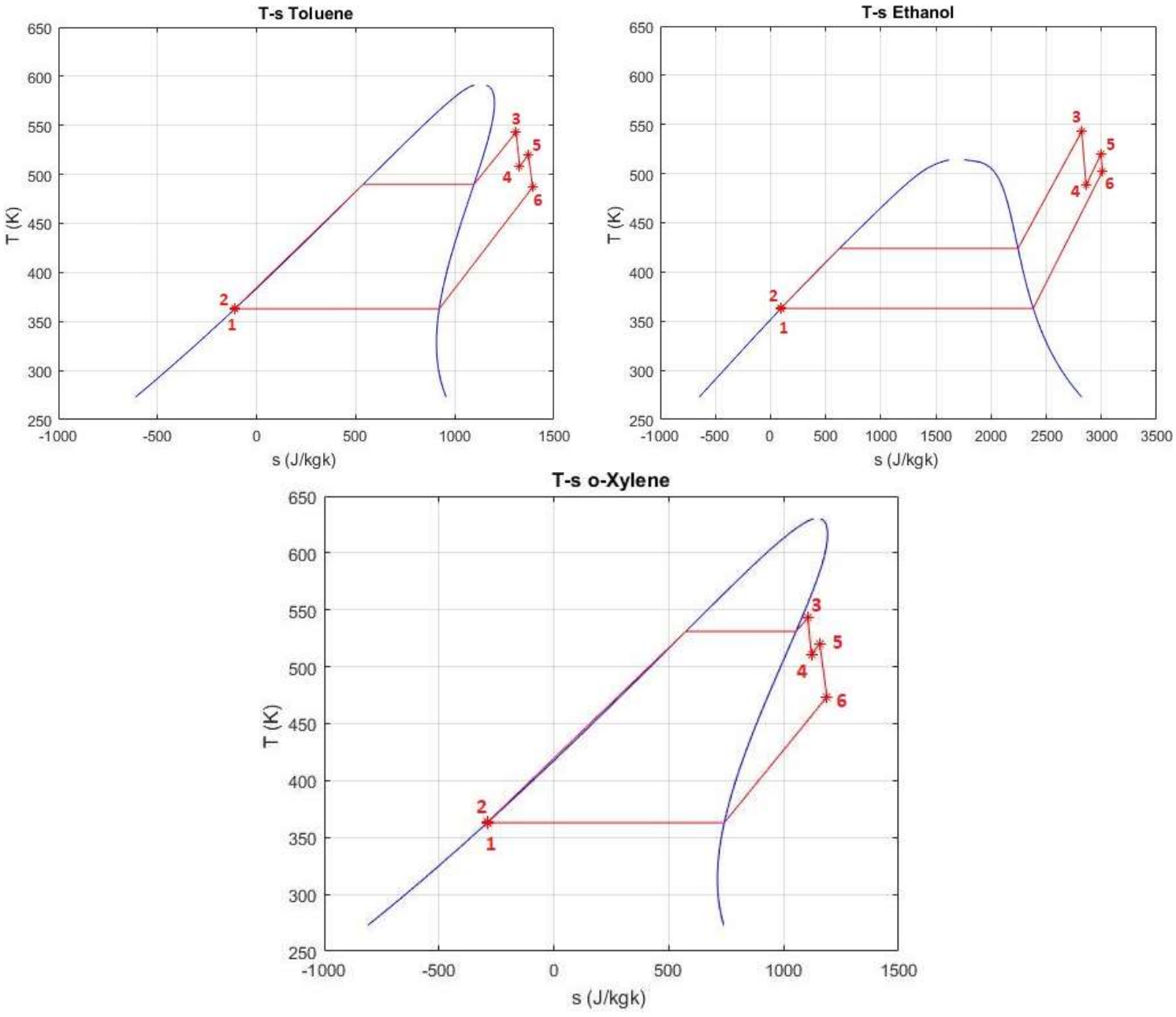


Figure 33: T-s diagram comparison between o-Xylene, toluene and ethanol at 543K maximum process temperature for reheated configuration

According to literature, reheating and turbine bleeding are not suitable in general for ORCs as the small gain that can be appreciated in the T-s diagrams of Figure 33 are expected not compensate the additional costs and increased complexity. This improvement measure would have a better application for cycles working at very high pressures. A very high pressure at turbine inlet means higher thermal efficiency but also higher moisture content so in modern steam power plants and reheating is a common solution for this problem, but this is not our case. Our efficiency has decreased and it and the additional cost and complexity of this measure, would not compensate the small increase in power output.

On the contrary, recuperated configuration is said in numerous articles from literature to appear as the most promising solution finding equilibrium between cost and complexity and improved performance.

Again to simulate it, it requires additional input parameters from the simple configuration. Minimum temperature difference, or pinch point, has been set to 10K based on other studies on literature and taken into account that we have a medium temperature process, that there cannot be temperature crossovers between hot and cold streams and that the lower the pinch point the lower the energy cost, but it also increases capital costs as more area of heat exchanger is required [35].

Additional input parameters for recuperated case

Parameter	**Value**
Minimum temperature difference (K)	10

Table 11: Additional input parameters for recuperated configuration

The simulation has given the results presented in Table 12.

Fluid	ηth (%)	Wnet (MW)
Toluene	18.972	1.054
Ethanol	13.623	1.374
o-Xylene	21.415	1.228

Table 12: Thermodynamic properties for maximum process temperature of 543K and recuperated configuration

Efficiency has risen for the three fluids with respect to simple configuration, increasing from 16% to almost 18.9% in the case of toluene, ethanol has risen from 11.7% to 13.6% and finally o-Xylene has achieved 21.4% efficiency while for simple configuration the value got was 18.4%.

Net power output is the same than in simple case as expansion is the same as before, it is just reducing the amount of heat needed to increase efficiency by using available heat. As it can be checked in Figure 34, heat from points 5 to 6, is yield to preheat the fluid from 2 to 3. Condensing pressure and vaporization enthalpies remain the same.

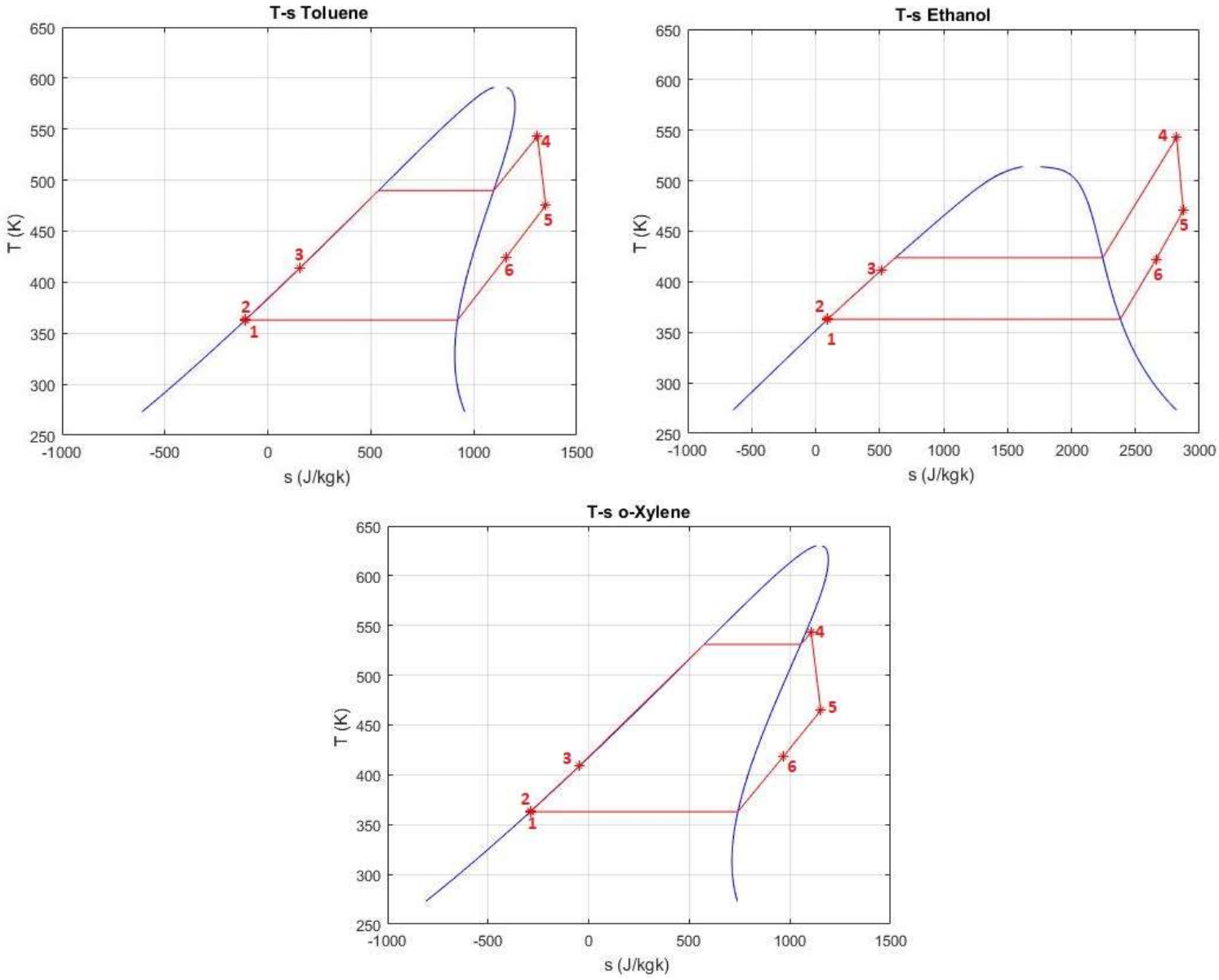


Figure 34: T-s diagram comparison between o-Xylene, toluene and ethanol at 543K maximum process temperature for recuperated configuration

The recuperator mainly increases thermal efficiency so that it keeps a high net power output but for a lower heat input as the liquid is preheated before entering the evaporator. Dryness at turbine outlet is 100%.

As other studies in literature reveal [28], highest efficiencies are obtained for fluids with less superheating, being the highest the ones expanding directly from the saturation vapor line. Appealing to Figure 34 this fact can be checked comparing it with results obtained in Table 12.

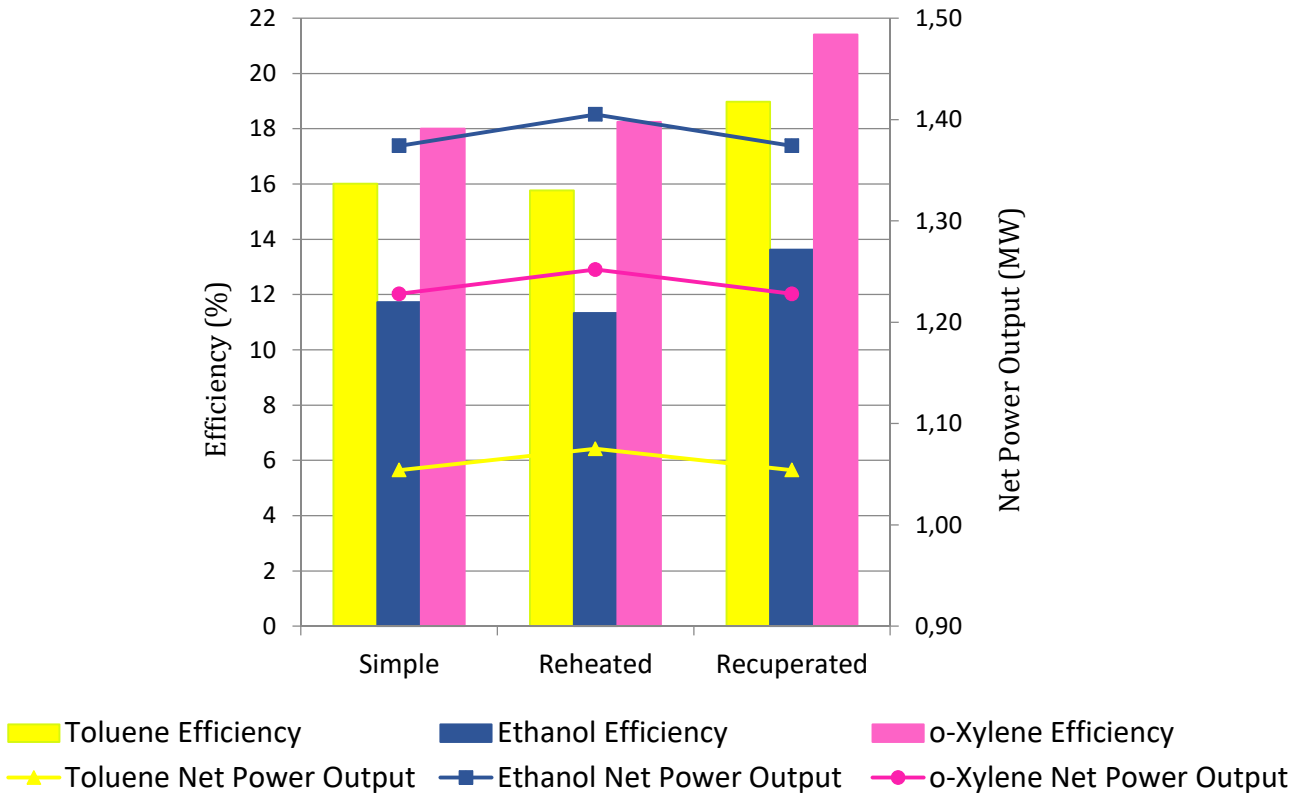


Figure 35: Efficiency and Net Power Output Comparison for the three configurations for Toluene, Ethanol and Pentane

Figure 35 presents the main results obtained in terms of efficiency and net power output for the three ultimate fluids under analysis for each of the configurations tested. It seems clear that looking for a compromise between efficiency and net power output, the fluid selected will be o-Xylene and the configuration chosen is the recuperated one as it remarkably increases efficiency for same power output.

By checking the constraints previously established, it can be found: on one hand that evaporation pressure is below critical pressure, so this condition is satisfied, dryness at

turbine outlet is above 90%, in fact it is 100% which it is the best result to expect and finally regarding melting temperature for o-Xylene it is -24ºC, temperature never reached in the selected location, so freezing risk is avoided.

Table 13, shows the properties through the ORC at design point and Figure 36 shows how the final layout of the process would be. Table 14 presents thermodynamic results obtained, where if compared with literature we find that efficiency obtained is slightly higher than the trend commented in ORC chapter, and that net power output is around the value expected.

Fluid properties at design point				
Point	**T (ºC)**	**P (bar)**	**h (kJ/kg)**	**s (kJ/kgK)**
1	90.00	0.54	-113.19	-0.28
2	90.38	10.00	-111.70	-0.28
3	136.03	10.00	-17.74	-0.04
4	270.00	10.00	555.77	1.10
5	191.68	0.54	431.45	1.15
6	146.03	0.54	350.54	0.97

Table 13: Organic fluid properties through the ORC

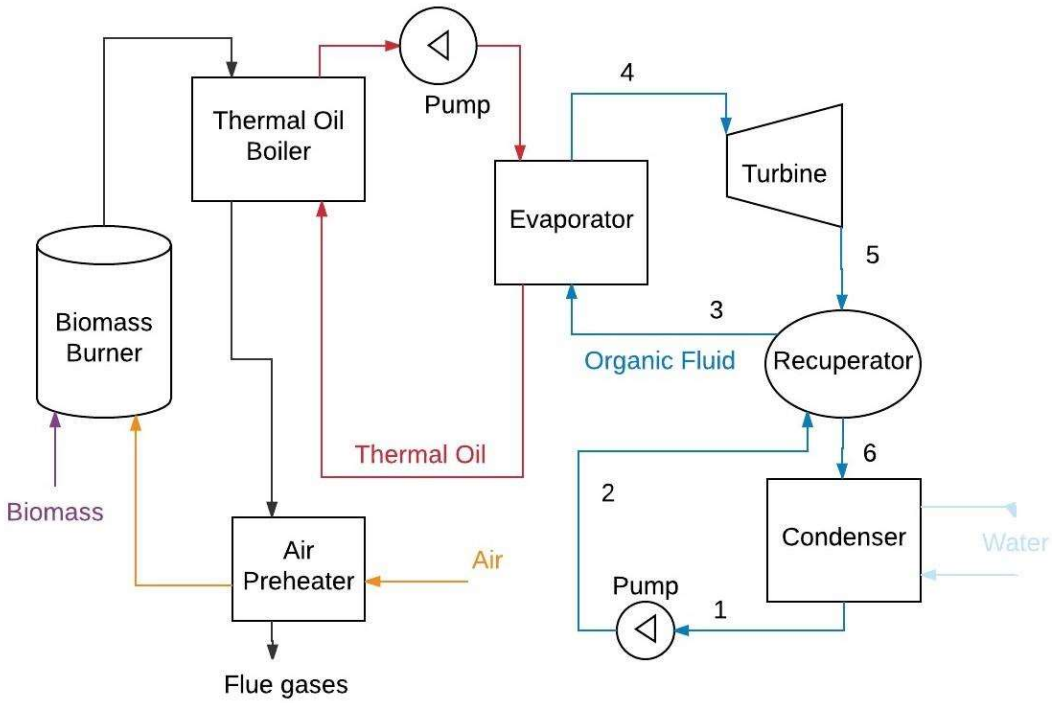


Figure 36: Final Plant Layout

ηth (%)	Wnet (MW)	Wturbine (MW)	Wpump (kW)	Qin (MW)	Qcond (MW)	Qrec (kW)
21.41	1.22	1.24	14.95	5.73	4.63	809.17

Table 14: ORC results

Another important parameter to calculate is the cooling water mass flow, which will be used for hot water supply as it will be further developed.

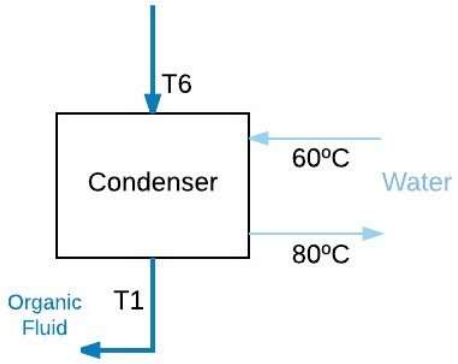


Figure 37: Condenser chart

As the condenser is a heat exchanger, an energy balance will be performed on it, the hot stream will be the organic fluid, and the cold stream will be the cooling water. Enthalpies at every point of the ORC process have already been calculated and assuming water specific heat as constant with temperature taking a value of 4.18 kJ/kgK, it can be found out the cooling water mass flow rate as cooling water enthalpies can be calculated in MATLAB using CoolProp because it is known both temperatures from Figure 37 and pressure which is set to ambient pressure.

Condenser energy balance	
Organic fluid side	$Q = m_{ORC} \cdot \Delta h = m_{ORC} \cdot (h_6 - h_1)$
Water side	$Q = m_{cw} \cdot (h_{cwo} - h_{cwi})$

Table 15: Condenser heat transfer equations

$$mcw = \frac{Q}{(hcwo - hcwi)} = \frac{m_{ORC} \cdot (h_6 - h_1)}{(hcwo - hcwi)} = 10.65\ kg/s$$

5. BOILER DESIGN

According to fuel selection it will be calculated O_2 requirements to determine the air to fuel ratio for the boiler by establishing a mass basis, as percentages are given in weight terms. Chemical composition of flue gases can be later calculated as well as boiler efficiency and, according to the useful heat requirements, we will finally find out the biomass amount needed for design point.

Although the scheme of the plant in Figure 36 represents separately burner from thermal oil boiler, we had designed it as same device for both processes as represented in Figure 38. In this device there will be two modules, combustion chamber module and heat exchanger module. Figure 38 represents the chosen biomass boiler for the ORC-biomass power plant based on technology selected in section in 2.5): fire-tube, grate fire boiler.

Figure 38: Grate fire-tube boiler

Biomass boiler will be explained more in detail in order to understand its functioning before performing the necessary calculations. A simplify diagram of the complete boiler has been provided in Figure 39. Biomass burner could be divided into four principal systems: Fuel feeding system, the grate assembly, secondary air and a system for ash discharge.

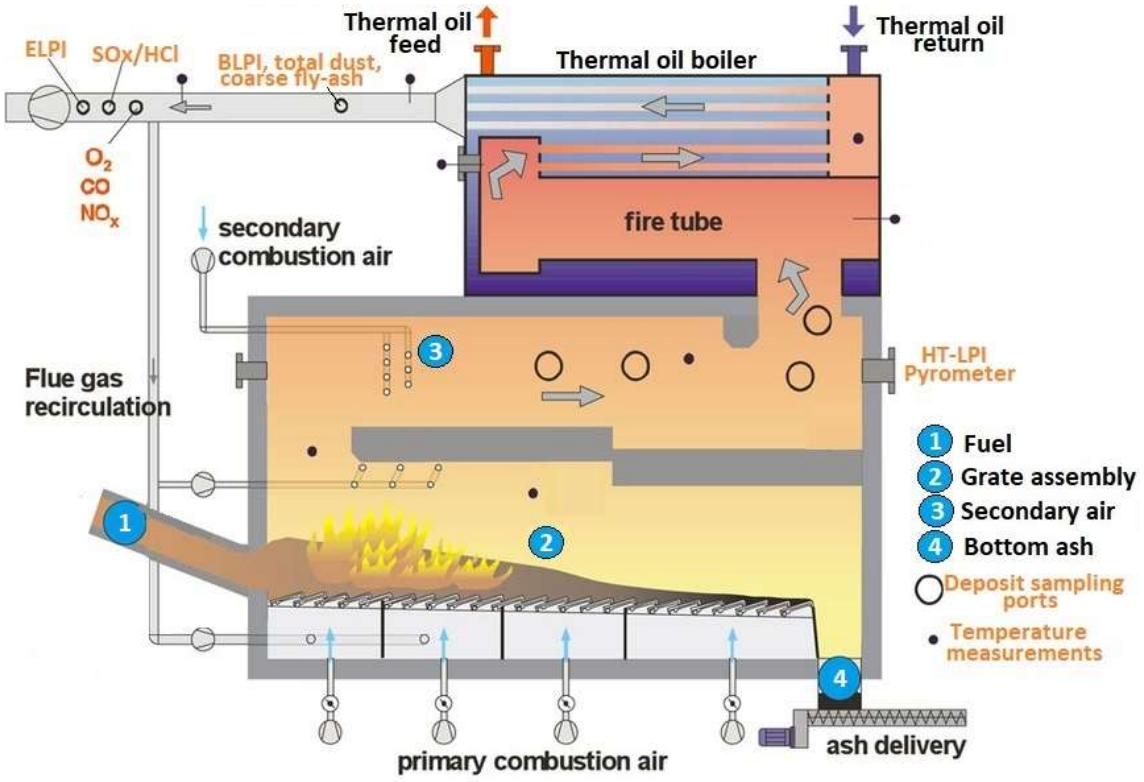


Figure 39: Biomass boiler scheme [36]

1) For fuel feeding system the plant will use a hopper as represented in Figure 40, together with a spreader to avoid fuel size segregation. The smaller particles will combust in suspension due to the primary air flows that we can observe in Figure 39 while heavier particles will fall and burn on grate surface. Wood chips will be brought from storage to biomass hopper through the conveyor belt selected for fuel transportation. The charging throat in Figure 40, will be water cooled to ensure long service life by protecting it from the heat from the furnace.
2) The grate assembly is located at the bottom of the combustion chamber. The type chosen for our plant will be a water-cooled vibrating grate, which according to [21],results appropriate for small scale boilers, as it spreads the fuel evenly with the advantage of having less moving parts than other movable grates, which reduces maintenance and increases life time. The grate has two main functions: longitudinal transportation of the fuel and distribution of primary air which enters beneath it as illustrated in Figure 39.
   Primary combustion air, which is released in some way perpendicular to biomass layer in the fuel bed, plays a key role in terms of efficiency and biomass complete combustion as it affects mixing and conversion fuel bed. Ignition of the fuel bed occurs by heating it through over-bed radiation and the refractory walls of the furnace. Once ignited, front propagates against the direction of the primary air provoking raw biomass drying and devolatilization.

If not all the oxygen is consumed in the reaction front, a char layer is formed above and when it reaches grate surface, a second reaction front is produced upwards bed surface, burning the char layer that had been generated. Figure 41 illustrates combustion chamber to represent this process.

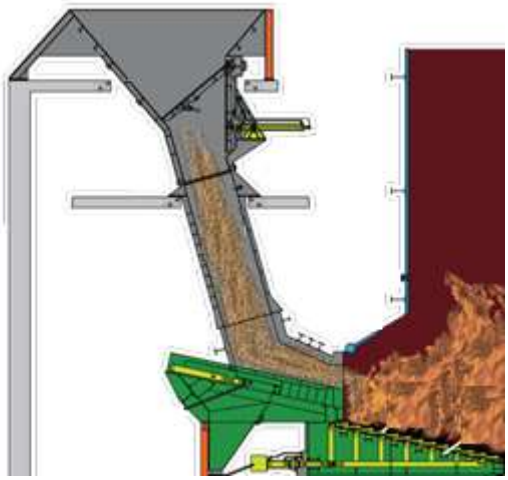


Figure 40: Fuel feeding system [37]

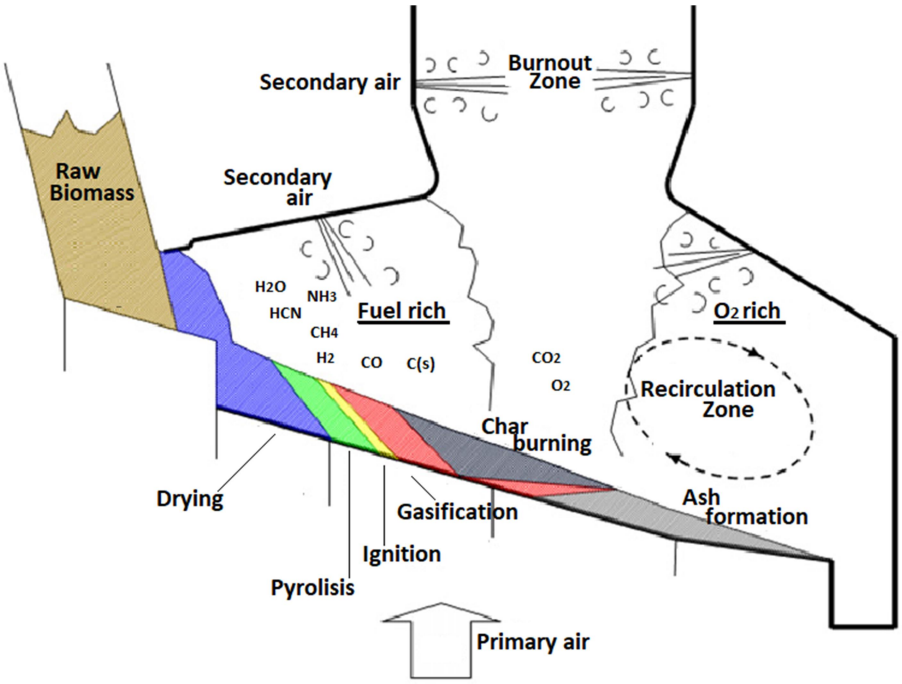


Figure 41: Combustion process in combustion chamber [36]

3) Secondary air supply function is to produce turbulence so to mix volatile gases favoring complete burnout, by increasing residence time and distributing temperature more evenly which leads to reducing emissions, especially NOx and CO. It is one of the most important elements for grate-fired boilers optimization.

4) Ash discharge system to transport sifting from beneath the ram to the ash discharge hopper.

After flue gases have heated the thermal oil flowing through the shell in the thermal oil boiler, it will pass to the evaporator as previously explained, to evaporate the organic fluid which will leave the evaporator at maximum design temperature selected, 543K. Although this project has not focused its interest in the evaporator design, a brief description has been included below.

The plant will use a shell and tube evaporator, as the one represented in Figure 42, where the organic fluid, which is the cold fluid, will flow through the shell while the thermal oil, the hot fluid, will pass through the tubes.

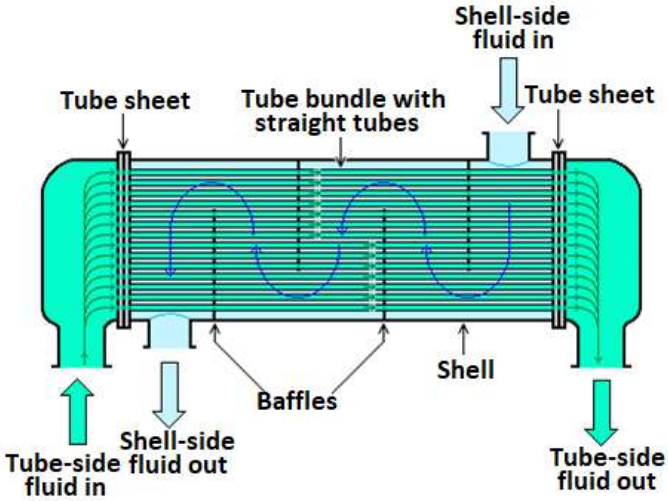
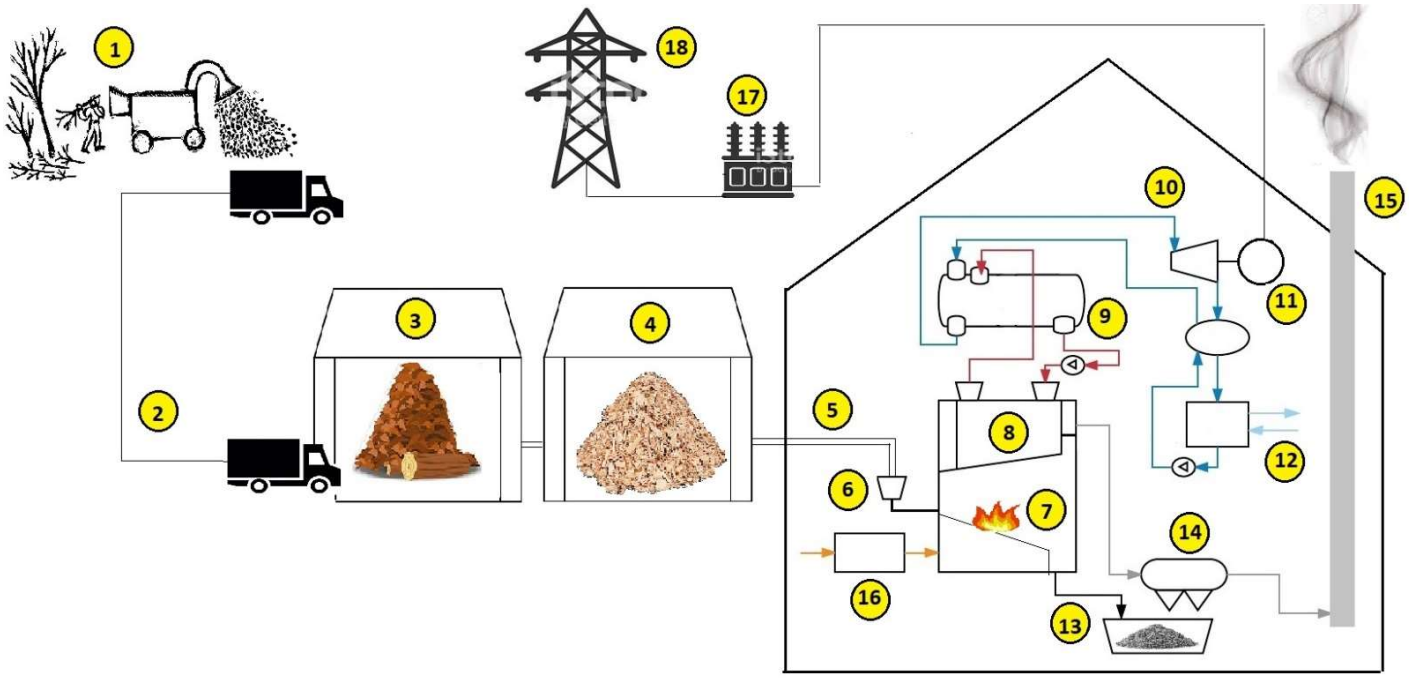


Figure 42: Straight tube heat exchanger (one pass tube side)

Pool boiling is supposed to occur in the heat exchanger. It consists on vapor generation from contact with a surface which is at higher temperature than the saturation temperature of the fluid which is o-xylene in this project case. Heated surface would be the walls of the tubes with the thermal oil flowing inside. These walls are small in comparison to pool proportions where they are immersed in initially stagnant organic fluid which motion will be induced by boiling progression.

At this point, most important processes for this project scope have already been developed and an scheme of the overall plant has been included in Figure 43 to clarify the whole plant functioning.



1.Wood cultivation, collection and chipping
2.Transportation
3.Evaluation and pretreatment
4.Storage
5.Transportation to the boiler
6.Hopper and dispenser
7.Biomass burner
8.Thermal oil boiler
9. Evaporator
10.ORC module (turbine, recuperator, condenser and pump)
11.Generator
12.Cooling water
13.Ash depository
14.Gases treatment (filter)
15.Chimney
16.Air preheater
17.Transformer
18.Grid

Figure 43: Overall plant scheme

The scheme provides a final overview of the complete installation functioning, with main components and/or processes listed below it.

From now on we will focus again in the boiler, which is the scope of this section, to perform the necessary calculations.

According to previous fuel selection, chemical composition to perform calculations is presented in Table 16.

C	47.1
$\mathbf{H_2}$	6.1
$\mathbf{O_2}$	44.2
$\mathbf{N_2}$	0.54
K	0.26
S	0.045
Cl	0.004

Table 16: Chemical composition in % ash free dry weight for selected fuel [7]

For solid fuels calculations are performed on a mass basis, as these fuels analysis is generally available in mass percentages as in this case. According to biomass composition provided in Table 16, our reactants are:

$$C + H_2 + O_2 + N_2 + K + S + Cl$$

Nitrogen is considered inert in theory; although in reality it will form some NOx that we will not take into consideration for this analysis. Potassium and Chlorine are considered not to react with any of the other elements present. So finally we get the following combustion equations, where each constituent is considered separately via its own combustion equation.

1)

$$C + O_2 \longrightarrow CO_2$$

$$12\ \text{kg} + 32\ \text{kg} \longrightarrow 44\ \text{kg}$$

Which for 1kg of biomass fuel (taken as basis):

$$0.471 + 0.471\ \text{x}\ \frac{32}{12} \longrightarrow 0.471\ \text{x}\ \frac{44}{12} \quad [\text{kg}]$$

2)

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$$

$$2\ \text{kg} + 16\ \text{kg} \longrightarrow 18\ \text{kg}$$

Which for 1kg of biomass fuel:

$$0.061 + 0.061\ \text{x}\frac{16}{2} \longrightarrow 0.061\ \text{x}\ \frac{18}{2} \quad [\text{kg}]$$

3)

$$S + O_2 \longrightarrow SO_2$$

$$32\ \text{kg} + 32\ \text{kg} \longrightarrow 64\ \text{kg}$$

Which for 1kg of biomass fuel:

$$0.00045 + 0.00045\ \text{x}\ \frac{32}{32} \longrightarrow 0.00045\ \text{x}\ \frac{64}{32} \quad [\text{kg}]$$

We must take into account the initial presence of oxygen which will contribute to the oxidation, so we have to subtract it when calculating the oxygen required.

Results from these calculations are provided in Table 17, which values are expressed on kg per kg of biomass fuel.

Element	Mass	O_2 required	Products
C	0.471	0.471 x (32/12) = 1.256	0.471 x (44/12) = 1.727 (CO_2)
H_2	0.061	0.061 x (16/2) = 0.488	0.061 x (18/2)= 0.549 (H_2O)
O_2	0.442	- 0.442	-
S	0.00045	0.00045 x (32/32) = 0.00045	0.00045 x (64/32) = 0.0009 (SO_2)
N_2	0.0054	-	0.0054
K	0.0026	-	0.0026
Cl	0.00004	-	0.00004

Table 17: Results from stoichiometric calculations in kg per kilogram of fuel

So in total, the oxygen required to burn 1 kg of biomass = 1.256 + 0.488 – 0.488 + 0.00045 = **1.3025 kg O_2 / kg biomass**.

Now in order to calculate air necessary for complete combustion, we just need to know proportions of oxygen and nitrogen by mass in the air. We know that approximately, neglecting the presence of other gases that are present in much smaller quantities, air is composed by 21% by volume of oxygen and 79% of nitrogen and that these have 32 and 28 molecular weight respectively. If we convert these values to mass basis:

Component	Volume fraction	Volume fraction x Molecular weight	Mass fraction
Oxygen	0.21	0.21 x 32 = 6.72	0.233
Nitrogen	0.79	0.79 x 28 = 22.12	0.767
		Average air molecular weight = 28.84	

Table 18: Conversion of air composition from volume basis to mass basis

Therefore, for the calculated 1.3025 kg O_2 / kg biomass required, the corresponding amount of nitrogen would be calculated as:

$$1.3025 \text{ kg } O_2 \text{ x } \frac{0.767}{0.233} = 4.2876 \text{ kg } N_2$$

Then the stoichiometric air to fuel ratio then would be:

$$\text{AFR} = 1.3025 \text{ kg } O_2 + 4.2876 \text{ kg } N_2 = 5.59 \text{ kg air/kg biomass fuel}$$

Once obtained the stoichiometric air to fuel ratio, a 20% of excess air has been assumed because combustion is never ideal so in practice more air than theoretical must be supplied in order to completely burn all fuel.

Actual air supplied is calculated as:

$$5.59 \text{ x } 1.2 = 6.71 \text{ kg air/kg biomass fuel}$$

According to Table 17 the products we get are: CO_2 , H_2O , SO_2 , N_2 , K and Cl. We are burning in air excess so we will find as products the excess of O_2 and N_2 , this last one added to the initial amount present in biomass which was considered as inert.

Finally O_2 product accounts for: 0.2 x 6.71 x 0.233 = 0.312 kg/kg biomass.

N_2 product: 0.0054 + 6.71 x 0.767 = 5.151 kg/kg biomass as product. A summary of product results is provided in Table 18. Notice that humidity content in biomass has been taken into account. Biomass fuel selected has 10% moisture content, as previously stated, so kg/kg biomass of each product have been adjusted assuming this fraction of water remains inert during combustion. The adjustment has been done dividing each mass by 1.1 and in the case of H_2O it also has been added this 10% of the total mass.

Product	Dry kg/kg biomass	kg/kg biomass (10% humidity)	Molecular weight	kmol/kg biomass	% Volume
CO_2	1.727	1.57	44	0.035	0.148
H_2O	0.549	0.59	18	0.027	0.115
O_2	0.312	0.28	32	0.008	0.036
SO_2	0.0009	0.0008	64	0.00005	0.00005
N_2	5.151	4.68	28	0,167	0.698
K	0.0026	0.002	39	0.00006	0.0002
Cl	0.00004	0.00003	35.4	0.000001	0.000004

Table 19: Combustion products

Flue gas mass can be calculated adding mass for each of its constituents:

$$m_{fg} = 1.57 + 0.59 + 0.28 + 0.0008 + 4.68 + 0.002 + 0.00003$$

$$= 7.03 \text{ kg/kg biomass}$$

At this point we have to take into account that there is a certain amount of ashes, 2% in our case. This percentage must be taken into account when calculating the mass flow of biomass fuel we need for our plant.

An important parameter to be calculated is the thermal oil boiler efficiency. To calculate boiler efficiency two methods can be followed: direct and indirect method. For direct method (input/output) energy output and fuel input are measured so that:

$$\eta_b = \frac{heat\ ouput}{heat\ input}$$

But direct method requires reliable information on flow of fuel measurement that we do not have available, so indirect method is preferred in this case, as errors in measurements do not impact too much the efficiency. It is known as the heat loss method due to its calculation which consists on:

$$\eta_b = 1 - \frac{heat\ loss}{heat\ input}$$

Heat losses are mainly due to:

- ✓ Stack loss
  It is the largest lost in a fuel fired boiler and it consists of:
  - Dry gas heat loss: Energy carried by gas leaving the system

$$Q_{fg} = m_{fg} \cdot Cp_{fg} \cdot (T_{fg} - T_a)$$

- Moisture loss: due to moisture in fuel and hydrogen fuel content. It is already taken into account in NVC.
- Humidity loss: moisture content in air. It is going to be neglected.

✓ Radiation loss
It refers to the heat transfer by radiation and convection, and it is a function of the thermal insulation.

✓ Unburnt loss
It is a measure of how well the fuel is burnt.

✓ Unaccountable loss
It consists on miscellaneous heat losses.

Finally we get the expression:

$$\eta_b = 1 - \frac{heat\ loss}{heat\ input} = 1 - \frac{Q_{fg}}{Q_c} - \frac{Q_{rad}}{Q_c} - \frac{Q_{unb}}{Q_c} - \frac{Q_{misc}}{Q_c}$$

Where:

$$Q_c = m_f \cdot NCV$$

For the calculation of the boiler efficiency, we are going to assume a determined % of radiation, unburnt and miscellaneous losses. With respect to the unburnt loss, we are assuming complete combustion in the burner so they are neglected. Radiation losses for grate furnace are among 1.8-3.5%, so being conservative; the highest value is the selected one. For miscellaneous heat losses 1% is assumed based on carbon heat losses in [38].

$$\eta_b = 1 - \frac{heat\ loss}{heat\ input} = 1 - \frac{Q_{fg}}{Q_c} - \frac{Q_{rad}}{Q_c} - \frac{Q_{unb}}{Q_c} - \frac{Q_{misc}}{Q_c} =$$

$$= 1 - \frac{m_{fg} \cdot c_{pfg} \cdot (T_{fg} - T_a)}{m_f \cdot NCV} - \frac{\%l_{rad}}{100} - \frac{\%l_{unb}}{100} - \frac{\%l_{misc}}{100}$$

Figure 44 shows a simplified chart of the energy balance in the boiler, where red lines represent the thermal oil that flows through the heat exchanger shell and that will take the useful heat to further on transfer it to the organic fluid in the evaporator. Biomass

selected has a determined net calorific value, and for efficiency calculation mass basis of 1kg can be used. Air does not enter at ambient temperature, as it is preheated according to Figure 39. Air entering temperature is going to be set to 100ºC.

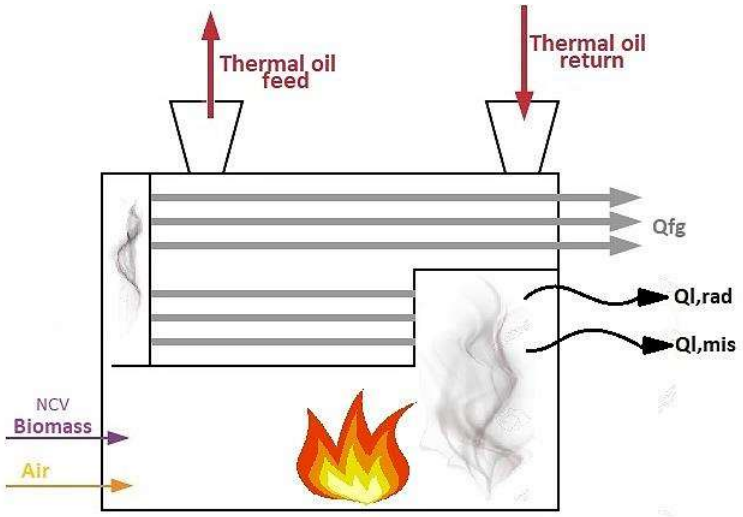


Figure 44: Boiler energy balance

With respect to the flue gases, we have already calculated its kg per kg of biomass fuel and its specific heat can be calculated from the equation below and using CoolProp Data Base in Matlab with the data previously obtained in Table 19 and setting the flue gases outlet temperature desired. Flue gases outlet design temperature at boiler outlet is going to be set to 300ºC in order to take the maximum advantage from them, reducing the heat losses, but also giving the possibility to use them for air preheating. According to [6], in most commercial power plants flue gases are not cooled below 120-180ºC as acid dew point must be avoided because of the presence of sulfur in flue gases. If this acid starts to condensate, the acid liquid produced could cause serious equipment corrosion problems.

To simplify calculations it has been neglected, SO_2 , K and Cl presence due to their low presence, so that they do not have a remarkable impact on c_{pfg}:

$$c_{\mathrm{pfg}} = \sum \left(\frac{\mathrm{m_i}}{\mathrm{m_{fg}}}\right) \cdot \mathrm{c_{pi}}(t_f) =$$

$$(1.57/7.03)\ \mathrm{x}\ 1.36 + (0.59/7.03)\ \mathrm{x}\ 2.817 + (0.28/7.03)\ \mathrm{x}\ 1.177 +$$

$$+ (4.682/7.03)\mathrm{x}1.281 = 1.44\ \mathrm{kJ/kgK}$$

At this point we already know all data necessary to calculate boiler efficiency as:

$$\eta_b = 1 - \frac{7.03 \cdot 1.44 \cdot (300 - 100)}{1 \cdot 18.4 \cdot 10^3} - \frac{3.5}{100} - 0 - \frac{1}{100} = 0.85$$

In order to calculate the useful heat needed, we must perform an energy balance in the ORC evaporator.

For that purpose properties from evaporator will be obtained. Thermal oil chosen is Therminol VP1. At design point, Therminol is going to enter the evaporator at 320ºC and exit it at 250ºC , we will assume no pressure drops occur in the process and 100% efficiency in the heat exchanger. These values for temperatures have been set in accordance with literature and already existing power plants [5], [29], [39], taking into account behavior of Therminol VP1 with temperature. Therminol VP1 specific heat value has been set to 2.3 kJ/kgK , taken from [40] for mean temperature between oil inlet and outlet temperatures.

Evaporator energy balance	
Organic fluid side	$Q = m_{ORC} \cdot (h_3 - h_2)$
Thermal oil side	$Q = m_{TVP1} \cdot C_{pTVP1} \cdot (T_{TVP1,i} - T_{TVP1,o})$

Table 20: Evaporator heat transfer equations

Knowing temperatures T_2 and T_3 which are noted in Table 12 from the simulation, and taking 1.97 kJ/kgK as value for o-xylene specific heat, which has been obtained from CoolProp Data Base at mean temperature between T_2 and T_3, we can solve for m_{TVP1}:

$$m_{TVP1} = \frac{m_{ORC\cdot} \cdot C_{pORC} \cdot (T_3 - T_2)}{C_{pTVP1} \cdot (T_{TVP1,i} - T_{TV\ \ ,o})} = \frac{10 \cdot (-17.74 + 111.7)}{2.3 \cdot (320 - 250)} = 5.8\ kg/s$$

From the equation using direct method for boiler efficiency calculation, we get:

$$\eta_b = \frac{heat\ output}{heat\ input} = \frac{m_{TVP1} \cdot C_{pTVP\ \ } \cdot (T_{TVP1,i} - T_{TVP1,o})}{mf \cdot NCV}$$

And then, mass flow rate of biomass fuel can be calculated as:

$$m_f = \frac{m_{TVP1} \cdot C_{pTVP1} \cdot (T_{TVP1,i} - T_{TVP1,o})}{\eta_b \cdot NCV} = 0.05\,\frac{kg}{s} = 207.5\,\frac{kg}{h}$$

6. FEASIBILITY ASSESMENT

For the feasibility assessment, an investment analysis is going to be performed, and the main criterion used will be the net present value (NPV). This method calculates the present values of all the benefits and costs of a project, also for the initial investment, and sums them to obtain the net present value of that project. If the net present value of the project is positive, according to this method, we should proceed with it and if it is negative we should not. Net present value is calculated according to the formula below, where B_t accounts for total benefits, C_t for total costs, n is the number of years of project life and finally i is the annual rate of interest.

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+i)^n} - \sum_{t=0}^{n} \frac{C_t}{(1+i)^n}$$

Lifetime and interest rate have been assumed according to other projects developed in Spain [41], [42] as 15 years and 6% respectively. Inflation will not be taken into account for this project so we are going to work with nominal interest rate instead of real one. Taxes on biomass have been estimated to be around 30%. A summary of this assumptions necessary to perform the NPV analysis have been summarized in Table 21.

Assumptions	
Lifetime	15 year
Operating hours	5000 h/y
Electricity selling price	60€/MWh
Interest Rate	6%
Inflation	Not considered. Working in nominal terms
Taxes	30%

Table 21: Assumptions for NPV calculations

Initial investment has been estimated from literature, knowing investment costs for a similar plant in Lienz [26], and adjusting it to current year and power [41]. These costs already include: ORC module costs, thermal oil module costs, electric work, engineering, installation, boiler, air preheater and others such as hydraulics. Value for investment costs has been finally set to 6,791,022€. Operation and maintenance costs as well as consumption and other costs have been listed in Table 22.

Annual Costs	
O&M	
Personnel	22,000 €/y
Plant Maintenance	228,000 €/y
Consumption Costs	
Biomass (15€/MWh)	90.000 €/y
Fluid	8,000 €/y
Other costs	
Insurance	5,000 €/y
Administration Costs	60,000 €/y

Table 22: Annual costs [26], [41]–[44]

Biomass yearly cost has been calculated assuming 5000 full load operating hours per year. For our 1.2MW and assumed price of biomass used in the plant of 15€/MWh power plant then:

$$1.2\ MW \cdot 5000\frac{h}{y} \cdot 15\frac{€}{MWh} = 90{,}000\frac{€}{y}$$

Revenues have two origins. We are going to sell the electricity we generate, which is the main objective of this project, but, aware that the trend indicates that sole electricity production is not feasible for these plants, water exiting the condenser will be proposed for hot water use with industrial purposes. One of the options proposed is selling hot water for a wastewater treatment plant. By using the tool [45] it has been found out that the closest wastewater treatment plant, which is the EDAR in Burguillos del Cerro, is located at less than 3km from the power plant location, so it would be an interesting option to supply them with the hot water they need to perform its function.

The closest wastewater treatment is e

- ✓ Electricity revenues are calculated according to Table 21, that establishes electricity price to 60€/MWh. Then:

$$1.2\ MW \cdot\ 5000\frac{h}{y}\ \cdot\ 60\frac{€}{MWh} = 360{,}000\ \frac{€}{y}$$

- ✓ Hot water price has been established according to the price of gas oil, which is assumed to be the current source for water treatment in a gas oil boiler. Therefore hot water selling price would be that of the gas oil used at this moment so that the wastewater treatment plant spends the

same money to perform same function but with the advantage and motivation of using a renewable source to do it. Assuming 0,11€/kwh [46] as the price for the central gasoil heating and an old gas oil boiler needing around 80 kWh to heat a cubic meter of water we get to know that the price of heating one cubic meter of water is around 8.8€, which means 0.0088€/L .

It can be calculated the total water that can be supplied as:

$$10{,}65\frac{kg}{s}\cdot 1\frac{l}{kg}\cdot 3600\cdot\frac{s}{h}\cdot 5000\frac{h}{y}=191{,}700{,}000\frac{l}{y}$$

And it is going to be assumed that all the water is sold. So the annual revenues that could be obtained by selling all the amount of hot water produced are:

$$191{,}700{,}000\frac{l}{y}\cdot\ 0.0088\frac{€}{l}=1{,}686{,}960\frac{€}{y}$$

Having calculated all benefits and costs, it can be calculated the NPV through the method previously explained, which is developed in Table 23. In this table we can check that a positive NPV of 4,134,000€ has been obtained so the project would result feasible for the conditions stated. NPV for just electricity generation, that is, not including hot water sale, has also been calculated and as expected a negative value, of -8,515.7€, has been obtained, in agreement with literature that stated that it would result non feasible.

It must be taken into account we have considered all hot water produced could be sold, but this assumption should be further studied. According to NPV method, this project would be feasible if at least 67.32% of hot water generated in the plant is sold, percentage at which NPV becomes zero (and calculated by trial and error).

	Year															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
COSTS																
Initial Investment	6791	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O&M	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Consumption	980	980	980	980	980	980	980	980	980	980	980	980	980	980	980	980
Insurance	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Administration	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
TOTAL	720,4	413	413	413	413	413	413	413	413	413	413	413	413	413	413	413
REVENUES																
Electricity	360	360	360	360	360	360	360	360	360	360	360	360	360	360	360	360
Hot Water	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9	1686.9
GROSS REVENUES	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9	2046.9
TAX (30%)	-614.08	--614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08	-614.08
NET REVENUES	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87	1432.87
CASH FLOW	-5771.1	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8	1432.8
NPV	-5771.2	-4809.0	-3901.3	-3045.0	-2237,2	-1475,1	-756.1	-77.8	562.0	1165.7	1735.2	2272.5	2779.3	3257.5	3708.5	4134.1

Table 23: NPV sheet with values in thousands €

Appart from the NPV, it has also been calculated the pay back period (PB) and the internal rate of return (IRR), in order to provide other investment analysis criteria.

The IRR is the interest rate at which the net present value of the project equals 0. It is commonly used to measure project attractiveness with respect to others. Ithas been calculated by trial and error according to the expression below.

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+IRR)^n} - \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^n} = 0$$

Result otained for the IRR is 15.68%. This value should be compared to the hurdle rate of the investor, which is the minimum rate of return the manager requires. If IRR is higher, then it should be a worthwhile investment according to this method.

The payback periodis the time required to recover investment cost. This method is really important for short-term perspective investors and when liquidity represents a considerable concern. It is calculated as initial investment divided by the annual cash inflow which would lead to a PB = 4.7 years, that is around 4 years and 8 months. We must take into account this method does not take into account value of money, and it ignores benefits occuring after this period meaning it is not a measure of profitability.

The values obtained in the investment analysis are quite favourable to proceed with the project, but should be further compared with other alternatives.

A more intense analysis should be dedicated to hot water selling fact, which was not the scope of this project, in terms of its viability and revenues get from it as it would constitute a critical factor for the decission regarding feasibility.

7. CONCLUSION

Energy from renewable sources appears as one of the most auspicious manners to achieve EU objectives regarding GHG emissions reduction and energy security improvement. Among renewable energies biomass appears to be a good substitute for fossil fuels in a near future as it has demonstrated to be a favorable option for electricity generation. In the project case, which is a biomass boiler working with an ORC instead of the conventional one using water as working fluid, cogeneration appears as a better option.

In this project a biomass CHP plant based on ORC technolody has been designed and analyzed. The central analysis has been focused on the ORC module in order to select the optimum fluid and configuration according to thermodynamic performance enhancement, as working fluid selection constitutes one of the key aspects of these power plants. The cycle has been designed setting maximum process temperature as the optimization parameter. The analysis carried out by MATLAB simulations using CoolProp Data Base, has set o-xylene as the best suited fluid for the cycle designed as it exhibits the higher thermal efficiency for an acceptable net power output which exhibits also one of the highest values. Best configuration has resulted to be recuperative one as expected from literature while reheated one has resulted unsuitable for the project scope. Efficiency obtained is in accordance with literature values and although it is still too slow compared with other technologies, if we compare it with literature results it exhibits a very competent value being among the highest ones. Although it is a very good result it must be kept in mind that differences may arise because of the difference in assumptions that in other cases may be more conservative. With respect to net power output it has also matched the expected result which was around 1MW.

In addition to the ORC process, the project has also focused its attention in the biomass boiler . After designing its architecture, according to current trends by the analysis of their main pros and contras, optimum air to fuel ratio and boiler efficiency have been calculated, being boiler efficiency around the expected value for the kind of boiler selected. Once known these parameters, and knowing useful heat needed by the ORC to work at design conditions from the ORC analysis previously carried out, mass of biomass required by the boiler has been obtained. This would constitute an important parameter, especially in terms of source availability for the plant future development, which may lead to a shift to other biomass sources.

A final plant design has been provided according to the analysis carried out, including a power plant scheme that includes most important processes and equipments necessary for the power plant functioning.

Aware that feasibility is one of the main concerns for this kind of projects, an economic analysis has been carried out in accordance with three different criteria: NPV, PB and IRR. According to these criteria the project would result feasible for the conditions established, but these conditions are based on assumptions so that changes in these assumptions would considerably impact results obtained. Sole electricity production for plant designed has been checked and result unfeasible as its NPV, which is the main criteria we are using, would result negative. This result is also in accordance with literature.

Therefore it is clear that steam rankine cycles are still preferred when designing biomass power plants just to produce electricity due to its increased efficiency as in ORCs losses are still too high.

An attractive option would be studying ORC application to already existing biomass power plants, but as waste heat recovery for which working temperatures would result much lower making ORCs very appropriate for it.

In spite of this, if cogeneration is implemented, the project seems an interesting option to take into account as soon as conditions for selling hot water are further analyzed, going for small scale power generation coming from renewable sources rather than large scale power generation currently driven mainly by fossil fuels.

8. APPENDIX

8.1) Nomenclature

AFR	Air to Fuel Ratio
CHP	Combined Heat and Power
c_p	Specific heat
cw	Cooling Water
EU	European Union
FC	Fixed Carbon
IEA	International Energy Agency
G	Generator
GHG	Green House Gases
GWP	Global Warming Potential
h	Specific Enthalpy
HP	High Pressure
IRR	Internal Rate of Return
LHV	Lower Heating Value
LP	Low Pressure
m	Mass flow
m-Xylene	meta-Xylene
NCV	Net calorific value
NFPA	National Fire Protection Association
NG	Natural Gas
NPV	Net Present Value
O&M	Operation and Maintenance
OPD	Ozone Depletion Potential
ORC	Organic Rankine Cycle
o-Xylene	ortho-Xylene
P	Pressure
PB	Pay Back
p-Xylene	para-Xylene
Q	Heat
s	Specific Entropy
SRC	Steam Rankine Cycle
T	Temperature
TVP1	Therminol VP1
th	Thermal
VM	Volatile Matter
W	Power
η	Efficiency

8.2) Software

7.2.1) Bionline

Bionline is a software developed by the Spanish IDAE “Instituto para la Diversificación y Ahorro de Energía ”, which is established in a biomass potential evaluation framework, regarding biomass origins and their possibility to be introduced in the energy market, and also according to their estimated costs and market availability.

The user can select a determined geographic area for the software to quantify its biomass source by selecting its origin which can be according to the software: remains from forest use, remains from agricultural crops and biomass coming from masses susceptible of implantation in both agricultural and forestry land. Link for Bionline Manual and Bionline Tool, is provided in [22].

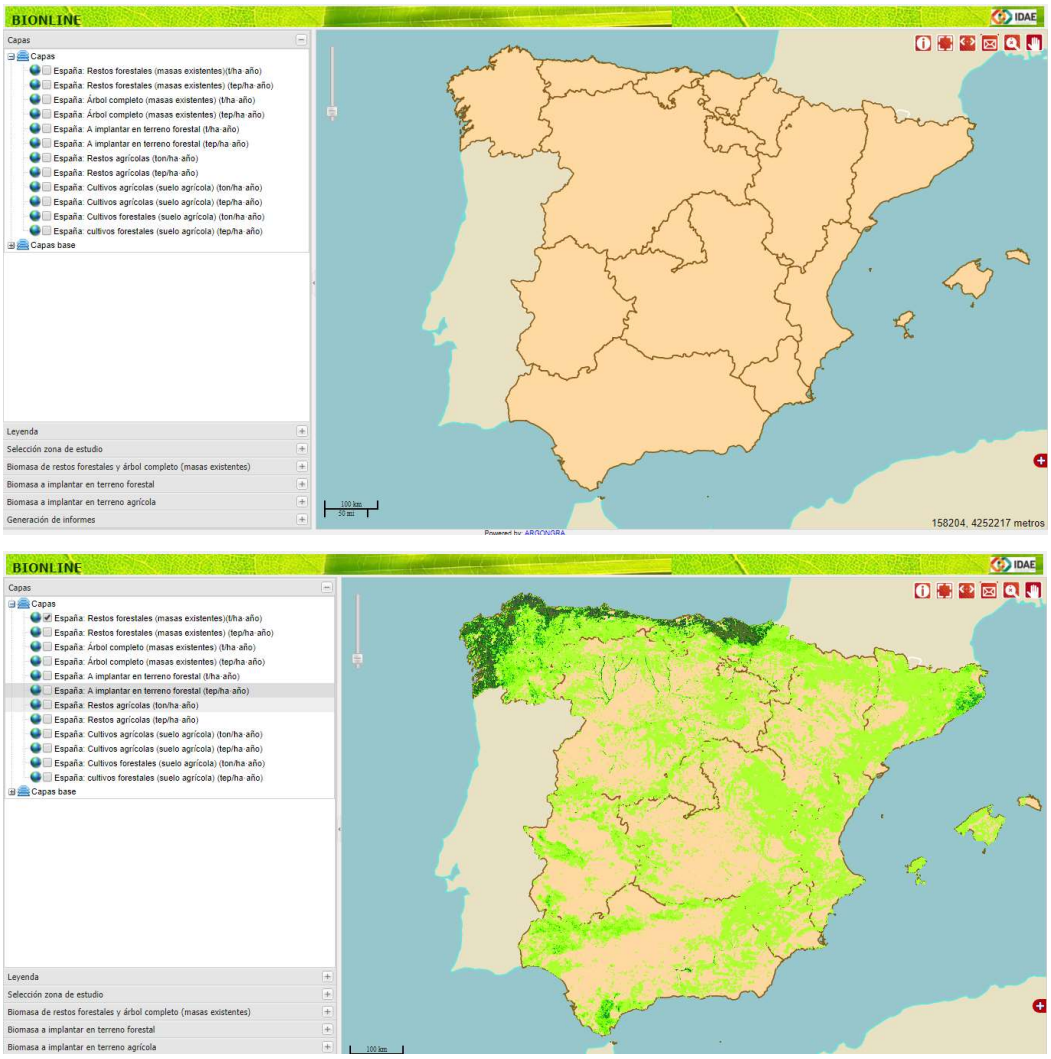


Figure 45: Bionline tool view

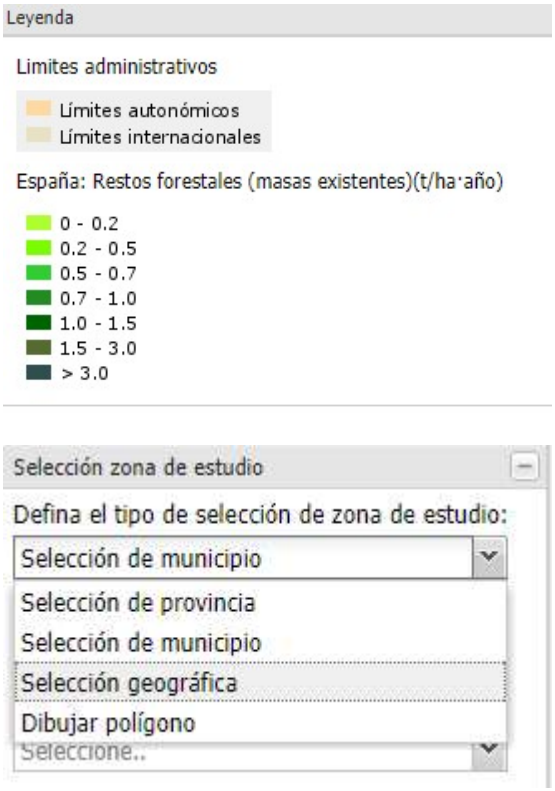


Figure 46: Bionline tool features

7.2.2) CoolProp

CoolProp is software that can be incorporated to other mathematical software such as MATLAB, Mathcad, Python or Excel, among others, as an extension to allow calculating thermodynamic properties of a series of fluids. By knowing some of the properties of the working fluid, this software allows to get the remaining properties that may be needed for the cycle modelling. This project has used CoolProp C++ library in Matlab by mainly calling PropsSI function, although there exist more functions that are not within this project scope. More information about this software can be found in [47].

8.3) NFPA 704M label

It consists on a system which purpose is to easily and simply provide a way of recognizing specific hazards of a material when an emergency situation occurs by rating them from 0 to 4 according to their severity. These hazards refer to: health (blue), flammability (red), instability (yellow) and special hazards (white). Although this is an American standard, established by the National Fire Protection Association, it has been decided to be used in this project as it is a clear and reliable way to provide a reference for the comparison of fluids in terms of security. In the Figure below, a guide to understand rating number for each hazard has been included.

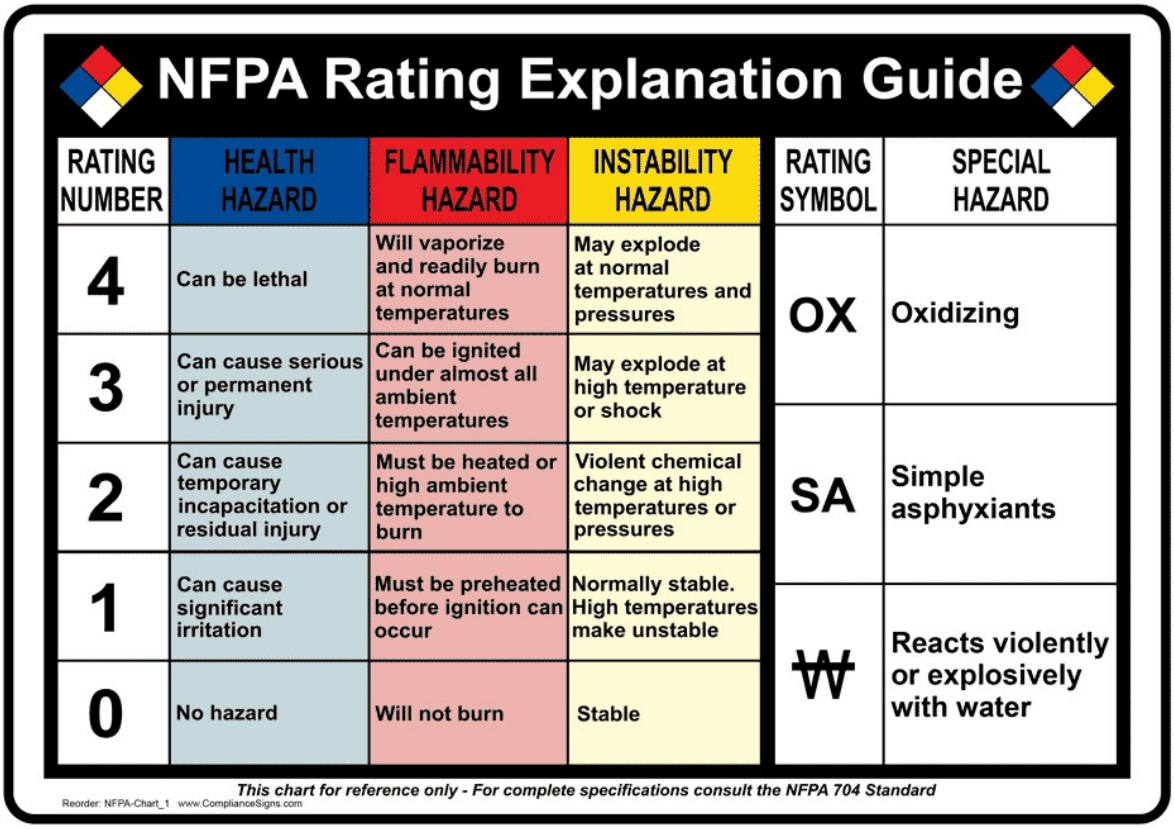


Figure 47: NFPA 704M Rating Explanation Guide

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